Exhibit A

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Analysis of the 35x35 MHz Band Plan Proposal for 600 MHz Spectrum

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Executive Summary

This whitepaper presents an analysis of the technical feasibility of the 35x35 MHz band plan proposed by T-Mobile, USA for the 614-698 MHz band. The plan occupies a total of 84 MHz of spectrum beginning at 614 MHz, the upper boundary of channel 37, and continuing to 698 MHz, and includes a 4 MHz guard immediately adjacent to channel 37 and a 10 MHz duplex gap between downlink and uplink.

The analysis was conducted by developing a set of core evaluation criteria based on principles put forth by the FCC in its October 2012 NPRM and by industry in its January 2013 letter to the FCC on *Expanding the Economic and Innovation Opportunities of Spectrum through Incentive Auctions.*

The core evaluation criteria can be summarized as follows:

- Utility and Quantity:
    - Maximize the traffic capacity available to users, and maximize the opportunity for wireless service providers.
    - Provide for equal amounts of uplink and downlink spectrum.
- Technical Feasibility and Cost Competitiveness
    - Utilize current technology, or employ technology advances that can expected to be achieved in 2014-2015.
    - Achieve technical performance that does not significantly impact traffic capacity or user operation, and can be provided at competitive cost.
- Do No Harm
    - Avoid, eliminate or render inconsequential, interference with incumbent users such as cellular or broadcast TV.
- Interchangeable Spectrum Blocks.
- Harmonized and Interoperable Band Plan.

Where technical performance issues are identified, the analysis seeks to identify feasible solutions that mitigate or eliminate any adverse effects.

The results of the analysis reveal that the 35x35 MHz plan shares several technical issues in common with other proposed plans, none of which prevents successful operation or deployment. These issues include:

- Interference due to TV Operation in the uplink segment of the band.
- The size of the Duplex Gap and the types of operation allowed in the gap.
- The guard band size required to protect the cellular operations from broadcast TV operations.
- The need to address interference between cellular and TV operations in geographically adjoining and national border regions.
- Maintaining equal relative value of the spectrum blocks.

Importantly, similar to other band proposals, the 35x35 MHz plan removes technical issues inherent to the FCC proposed band plan, in particular, spectral inefficiency and inter-modulation distortion potential resulting from operation of broadcast TV in the duplex gap.

The analysis has also identified performance characteristics unique to the 35x35 MHz plan compared to other plans. The most important of these characteristics is the achievement of a nominal 40% increase in wireless broadband capacity compared to a 25x25 MHz band plan. Other characteristics associated with the 35x35 MHz band plan involve issues of handset antenna performance, duplex filter feasibility, and the potential for harmonic interference with a portion of the existing PCS bands. Our analysis shows that current technology or technology improvements expected by 2014-2015 can resolve, or substantially mitigate, any performance issues that result from the 35x35 MHz configuration T-Mobile has proposed. The challenges associated with the 35x35 MHz configuration, their related performance issues, and resolution approaches are summarized below:

Technical Question	Performance Issue(s) or Concern(s)	Resolution Approach(es)	Result
Single device antenna covering wide bandwidth	• Antenna Length Increase causes -0.32 dB detuning • Antenna efficiency causing degraded detuning of -0.6 dB • Larger antenna size compatible with handset	• Optimize antenna for 600 MHz uplink • Increase base power • Advanced antenna design	• Capacity significantly exceeds other plans • Negligible throughput decrease • Minor antenna structure size increase-compatible with (4-5 inch smartphones) • Advanced antenna designs resolve issues
Duplex Filter	• Sufficient Transmit /Receive Isolation in Handset	• Overlapping duplex filter structure • Advanced duplexer materials	• Acceptable performance achieved • Slight cost increase mitigated by unit volumes • Advanced duplexer approaches resolve issues
Harmonic Interference	• 3.5% Interference with PCS band receiver (3rd harmonic) • Minimal Interference with BRS band (4th harmonic)	• Frequency coordination • Improved RF harmonic filter	• No degradation to PCS or BRS band device or user

Again, taking these challenges into account, the 35x35 MHz band plan still achieves a nominal 40% capacity increase compared to a 25x25 MHz band plan and an effective spectrum utilization efficiency of 88% (70 MHz out of 80 MHz including the duplex gap).

Positive attributes of the 35x35 MHz plan shares with other band plans include:

- Creating 5 MHz paired interchangeable FDD blocks
- Allowing channel 37 (608-614 MHz) to continue to be used for medical and other unlicensed applications and
- Providing a total of 10 MHz guard band for broadcast TV channels below 37 (608 MHz)

Other characteristics that the 35x35 MHz band plan shares in common with other proposed 600 MHz band plans, including 25x25 MHz and 30x30 MHz band plans, include:

- The downlink band (618 - 653 MHz) is intended to be reserved in all geographic areas. However in the uplink band (663 – 698 MHz), TV stations may still be allowed to operate in some geographic regions, with the guard band used to protect cellular operations in these regions
- Impact of less spectrum freed up in uplink region in certain geographic and border areas:
    - Mitigation through geographic isolation, co-siting, antenna orientation coordination
- Impact of 600 MHz operation on size of the device antenna:
    - 10% larger than 700 MHz Operation
- Concurrent support for multiple bands, e.g., 700 MHz, AWS, PCS
- The spectrum below channel 37 (608 MHz) can be used for TV transmission, Supplementary Downlink (SDL), or as unpaired LTE using Time Division Duplex (TDD) technology
- Duplex gap can be used in a secondary fashion for unlicensed and other non-interfering applications

The analysis shows that none of the challenges in the above characteristics impose technical requirements which cannot be met using current technology.

In summary, the technical performance requirements of the 35x35 MHz plan can be met by current and reasonably anticipated emerging technologies. The 35x35 MHz band plan provides the largest amount of broadband wireless capacity compared to the other band plans that have been proposed. Instead of being limited by current traditional technologies, it leverages anticipated technical advances and offers a longer range, cost effective solution for the 2014/2015 timeframe.

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1.0 Introduction

In response to the FCC NPRM document released in October 2012 [FCC], several comments and Band Plan proposals have been submitted. T-Mobile proposed a 35x35 MHz Band Plan as an effective solution for maximizing the benefit to the end customers and providing a competitive landscape to the operators [TMOB1]. This study provides a technical analysis of this Band Plan proposal.

1.1 600 MHz Incentive Auction

The FCC initiated action via an NPRM describing its intent to conduct an incentive auction to re-claim broadcast TV spectrum in the 600 MHz band and re-allocate that spectrum to commercial broadband wireless service. The intent is for the DTV operators to vacate, using a reverse auction approach, a range of spectrum starting downward from 698 MHz, and for the cellular operators to introduce LTE based services (forward auction) in the vacated spectrum. Additional background on the proposed action is summarized as follows:

- The FCC included a proposed band plan in its NPRM
- FCC enumerated basic principles in the NPRM: “utility, certainty, interchangeability, quantity, and interoperability ” and assignments of blocks in 5 MHz sizes
- Several organizations have submitted responses to the FCC NPRM, critiquing the FCC Band Plan, and offering criteria/principles for developing a high value approach
- Organizations have also submitted their own band plans intended to overcome technical issues including co-existence with broadcast TV and other cellular systems.
- T-Mobile submitted a response to the FCC proposing a 35x35 MHz band plan

1.2 Purpose and Scope of the Whitepaper

The intent of this whitepaper is to evaluate the technical merits of the 35x35 MHz band plan proposed by T-Mobile. [TMOB1]. The T-Mobile proposal uses the core principles arrived at as a consensus between NAB, cellular operators, and product suppliers [ATT2] and suggests that the approach addresses technical issues including various types of interference, spectrum usage efficiency, and complexity of antenna and filter designs.

1.3 Organization of the Whitepaper

The framework including requirements for an effective Band Plan meeting the FCC criteria and the industry consensus is provided in Section 2. The 35x35 MHz Band Plan proposed by T-Mobile is reproduced in Section 3 for the sake of completeness. Section 4 provides a detailed analysis of the 35x35 MHz band plan in terms of its strengths along with the key issues and mitigation approaches. The issues are segmented into two categories – those which are common and to be addressed by all other similar Band Plans for the 600 MHz spectrum, and the others which are primarily related to the proposed 35x35 MHz Band Plan. Section 5 provides concluding remarks summarizing the evaluation of the 35x35 MHz Band Plan and how it provides for the criteria set in Section 2. References cited in the study follow. Appendix A reproduces the representative 25x25 MHz and 30x30 MHz Band Plans that have been proposed during the NPRM responses to FCC. The Roberson and Associates company profile is provided in Appendix B.

2.0 Analysis Approach and Band Plan Evaluation Criteria

The overall approach to the analysis of the 35x35 MHz band plan is straightforward: identify the relevant evaluation criteria, and then assess the performance of the plan compared to those criteria. An effective and practical band plan would meet the evaluation and performance criteria thus established.

The criteria used were derived from two external sources: the October 2012 FCC "Incentive Auction" NPRM [FCC], and the January 2013 industry "Letter to the FCC" [ATT2]. The criteria contained in these sources were then consolidated into a set of "core criteria," to which additional items addressing technical feasibility and cost/competitiveness issues were added. The FCC criteria, industry criteria, and core criteria are described in detail below. Together, these constitute the framework or reference for evaluation of the 35x35 MHz band plan.

2.1 FCC Criteria

The FCC has provided a set of fundamental principles in its NPRM which forms the foundation for developing and evaluating band plans. A sound interpretation of these items is provided in [ATT1], and is summarized and restated below along with some additional clarification:

<u>FCC Criteria</u>

- Utility: maximize the capacity and utility (value) of the available spectrum. This implies that the bandwidth allocated to the LTE cellular operations and the spectrum usage efficiency need to be maximized with appropriate trade-offs in implementation feasibility and complexity. It is also necessary that the interference impact to incumbent users be minimized.
- Certainty: provide potential spectrum license bidders with certainty as to the characteristics (performance potential) of the spectrum on which they are bidding.
- Interchangeability: develop spectrum blocks for operators that have *similar* utility (value) so that they are interchangeable from the point of view of the provider.
- Quantity: maximize the amount of spectrum bandwidth made available by the auction. For example, this would imply the largest potential operating bandwidth and least amount of overhead (due to guard bands or duplex gaps, for example)
- Interoperability: support allocation of spectrum in a manner that permits the development of band classes that support equipment and devices that can be used nationally as broadly as possible.

2.2 Industry Criteria

Several of the key stakeholders recently sent a consensus document stating its core principles regarding the incentive auction spectrum to the FCC [ATT2]. These principles were based primarily on an analysis of the band plan proposed by the FCC in its NPRM. They identified the technology implications of the FCC plan and suggested band plan principles that avoid certain technical challenges. The industry criteria are listed below:

Industry Criteria

- Adopt a contiguous “down from Channel 51” approach with uplink at the top of the band and continuing downward from 698 MHz
- Maximize the amount of paired spectrum above TV 37 (rely on supplemental downlink configurations where spectrum is cleared but pairing options are not viable). These unpaired supplemental downlink blocks can be used in concert with currently defined uplink bands in the 700 MHz and PCS bands etc.
- Rely upon 5 MHz spectrum blocks as building blocks for the band plan
- Incorporate a “duplex gap” or spacing between uplink (mobile transmit) and downlink (base transmit) of a minimum of 10 MHz, but no larger than technically necessary.
    - Uplink and downlink filter feasibility dictates a small size limitation
    - Large duplex separation has adverse impact on antenna design [RIM] and user device size [ATT1]
- Avoid broadcast television stations in the duplex gap. This avoids various potential interference scenarios. Use of guard bands increases the duplex gap and reduces the amount of spectrum available for wireless operation.
- Preclude any operations in the duplex gap or guard bands that would result in harmful interference to adjacent licensed services
- Provide guard bands that are consistent with the principle “no larger than is technically reasonable” to guard against harmful interference between adjacent operations.
- Provide a guard band between a high power broadcaster and mobile downlinks that is sufficient to protect the wireless service from interference, which will likely be larger than the 6 MHz proposed by the FCC
- Permit existing operations in TV 37 to remain. This includes the Wireless Medical Telemetry System (WMTS) and radio astronomy applications
- Facilitate international harmonization, prioritizing harmonization across North America, and move forward expeditiously to coordinate with Canada and Mexico for new broadcast assignments. Harmonization would provide enormous benefits to consumers in terms of reducing costs and increasing the availability of services [RIM]. The primary implication of this requirement is on the duplex gap to be in the 10-14 MHz range as the accepted norm and on mitigation of co-channel and adjacent channel interference for the cellular operation.

2.3 Core Criteria

The following core criteria, derived from and in addition to above sets of criteria, constitute the framework for evaluating the 35x35 MHz band plan.

Utility and Quantity

- Maximize spectrum utilization efficiency to maximize capacity and benefit for users
- Provide largest amount of spectrum capacity for broadband wireless service
- Provide for supplementary downlink (SDL) spectrum below channel 37 starting downward at 608 MHz as appropriate. SDL can also be adjacent to the core downlink spectrum [MOTO]. SDL can be used in concert with either the 600 MHz core operation or to supplement the downlink for cellular operation in other bands

Technical Feasibility at Competitive Cost

- Technical performance, especially relating smartphones and tablets for the major hardware components, including filters, duplexers, tuners, and antenna systems, should be consistent with 2014-2015 availability [QUAL1], and be cost competitive
- Optimize uplink performance (efficiency) over downlink, if necessary, since uplink power is limited and the base stations have more range and capabilities for higher power transmission
- Single device antenna structure for operating bands < 1 GHz
- Minimum duplex gap resulting in a much smaller antenna bandwidth and, therefore, a simplified antenna design [MOTO].

Do No Harm

- Avoid, eliminate or render inconsequential, any adverse effect of harmonics due the 600 MHz LTE uplink transmitter limitations.
- Avoid, or render inconsequential, broadcast TV coexistence (interference) issues.

Interchangeable Spectrum Blocks

- Keep the downlink spectrum band consistent nationwide and a fixed allocation for the downlink that is cleared of all broadcast stations nationwide [FCC], [CEA], [MOTO]. This minimizes the space and power requirement for downlink filters in mobile devices and helps ensure interoperability across the band [RIM].
- Flexible enough to accommodate varying amounts of spectrum relinquished from the incentive auction process in different locations.

Harmonized /Interoperable Band Plan Approach

- The band plan needs to be consistent with the use of advanced LTE techniques including carrier aggregation and Multiple Input Multiple Output (MIMO) and other Advanced LTE Release 10 features.

3.0 Description of the 35 x 35 MHz Band Plan

After introducing the basic terminology relevant to a band plan analysis, this section describes the 35x35 MHz plan proposed by T-Mobile USA. The plan provides for commercial broadband wireless operations in the 600 MHz band, using spectrum made available via an incentive auction. The band plan was devised with the intent of satisfying the FCC and industry criteria described in Section 2, in particular, maximizing the available full duplex bandwidth to users and operators in the spectrum region above Channel 37.

3.1 Band Plan Reference Terms

In order to provide a reference for the description and analysis of the band plan, the key terms used in this whitepaper are illustrated in Figure 1. These terms (technical parameters) include: center frequency of operation, pass band width, duplex gap, and total operating bandwidth. Downlink and uplink refer to the spectrum used for downlink (base station to user device), and uplink (user device to base station) communications, respectively.

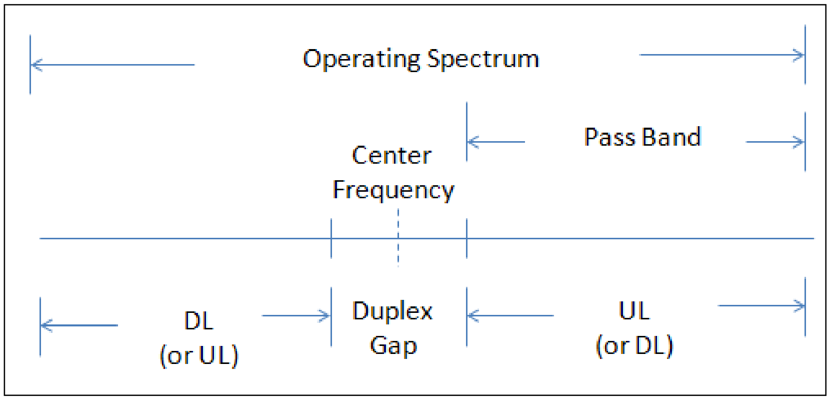

Figure 1: Cellular Band Plan Parameters

Spectrum usage efficiency is defined as (DL + UL)/ Operating Spectrum

3.2 35x35 MHz Band Plan

The specific 35x35 MHz band plan proposed by T-Mobile [TMOB1] and the subject of further analysis is illustrated in Figure 2. The band has its 35 MHz uplink defined from 698 MHz downward, followed by a duplex gap of 10 MHz, a 35 MHz downlink, and a 4 MHz guard band, ending at 614 MHz.

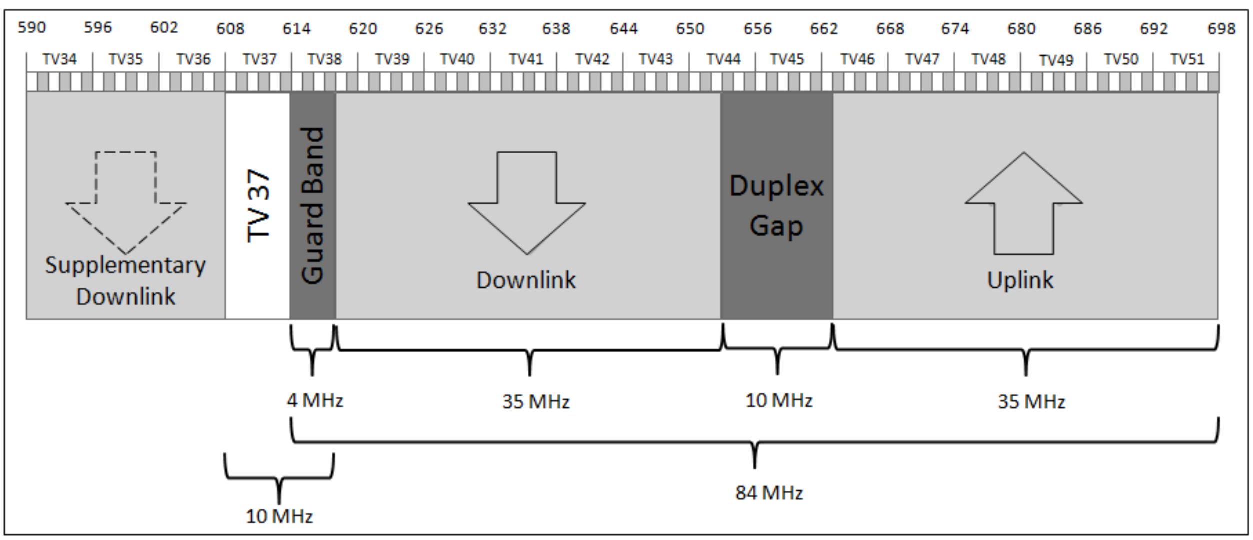

Figure 2: Proposed 35x35 MHz Band Plan

The 4 MHz guard band immediately above channel 37 enables an overall guard band of 10 MHz for any broadcast TV or other operations below 608 MHz. Since Channel 37 is being used for radio astronomy and intra hospital radio communications, these uses are not expected to cause measurable interference into the LTE system in the spectrum above 618 MHz.

The region below channel 37 (608 MHz) may be used for Supplementary Downlink (SDL) broadband wireless operations, TV stations, or LTE Time Division Duplex (TDD) operations. SDL is particularly suited for carrier aggregation or as supplemental downlink.

Section 4 describes the analysis of this 35x35 MHz band plan, along with the technical issues that need to be addressed in order to make this plan feasible. The issues are addressed in two categories, 1) those issues unique to this band plan due to its wider bandwidth, and 2) those issues which are common to all the band plans.

4.0 Analysis of the Proposed 35x 35 MHz Band Plan

Using the core criteria indicated in Section 2, an evaluation of the 35x35 MHz band plan was performed. Section 4.1 identifies the positive attributes of the plan and highlights the advantages, primarily related to the availability of a greater amount of spectrum. The requirement for a wide band plan in any spectrum region including 600 MHz spectrum may create issues primarily driven by current technology limitations and the potential for interference into other operating cellular spectrum.

Technical issues specific to the 35x35 MHz band plan (compared to other band plans) are identified in Section 4.2, along with solutions to mitigate performance issues where they exist. This facilitates introduction of the band plan into the market place. Additionally, issues in common with other band plans that introduce cellular LTE operation in the 600 MHz spectrum have been identified.[1] While most of these common issues have already been discussed in previous submissions to the FCC [ATT1], [ALU], [MOTO], [QUAL], [TMOB1], [VERI], the key issues, the estimates of their impact, and approaches to their resolution are summarized in Section 4.3.

4.1 Strengths of the Proposed Band Plan

The strengths of the 35x35 MHz band plan can be demonstrated by comparing its attributes to the core evaluation criteria.

<u>Utility and Quantity</u>

The major value of the 35x35 MHz band plan is its provision for the largest uplink and downlink pass bands, compared to other plans as described in Appendix A. This maximizes the capacity, spectrum bandwidth, and utility of the available spectrum. Simply stated, the band plan creates benefit for the largest number of users. Economies of scale due to high device volumes, and the motivation to develop technology improvements to optimize performance will provide low cost solutions for customers along with high throughput and capacity. The band plan also creates the greatest business opportunity for carriers, operators, and equipment suppliers and fosters a competitive environment. The auction of a wider spectrum range is likely to allow winning bids by a larger number of operators.

Another way to capture the value of the 35x35 MHz band plan is to carry out a comparison with the25x25 MHz band plan using key attributes like spectrum availability to users. In order to carry out a fair comparison, the 25x25 MHz band plan is also assumed to have a 10 MHz duplex gap

[1] Other band plans, representative of others that have been proposed for the 600 MHz band are described in Appendix A.

instead of 14 MHz [ATT1]. Also, the overhead of the guard Band below the band plan is not included in the calculations since the vacant spectrum region above channel 37 may be used for supplementary Downlink (SDL) or other low power unlicensed applications.

The 35x35 MHz band plan provides a nominal 40% increase in useable bandwidth (pass band) as a standalone band as compared to the 25x25 MHz plan and hence makes available a significantly larger amount of data capacity to end users. It utilizes an operating bandwidth of 80 MHz (including the Duplex Gap (DG) of 10 MHz) above channel 37 which is close to the upper limit of 84 MHz. The spectrum usage efficiency correspondingly improves from 83% to 88% as compared to the 25x25 MHz band plan since the Duplex Gap becomes a smaller percentage of the operating spectrum.

The characterization of the 35x35 MHz band plan is predicated on the assumption that technology will support the availability of the active pass band spectrum defined in the band plan. This is addressed in Section 4.2 where it is shown that solutions exist for the identified antenna, filter, and harmonic interference issues which can impact the effective pass band spectrum available to the users. The tradeoff in enabling a wider spectrum is expected to require marginally additional hardware, space, and cost.

4.2: Technical Issues Unique to the 35x35 MHz Band Plan and Their Resolution

Devising a new band plan is a challenging task that requires analysis and tradeoffs in the design of the transceiver components and technical performance necessary to operate successfully in the band. The key technical issues which have been determined to be in common for all the major band plan proposals for the 600 MHz spectrum, including for 35x35 MHz band plan, are described in the subsequent Section 4.3, along with technical approaches or solutions for mitigating unacceptable performance.

In this section, the key technical issues which have been identified as unique to the proposed 35x35 MHz band plan are described, and approaches to resolve or mitigate these issues are presented. In some cases the resolution approach entails use of interim viable solutions with a transition plan, as applicable, to take advantage of expected technology advances for more optimal longer term solutions. Planning for reasonably expected technology advances allows a band plan to be selected that is more efficient and effective than one based on a shorter term viewpoint that is strictly limited to currently available technology. A forward-looking approach will provide the maximum value to end users and operators.

The technical issues identified as posing a unique challenge for the 35x35 MHz plan include (1) antenna performance, which is closely related to user device size and cost; (2) RF duplex filter feasibility and performance; and (3) interference generated to other LTE bands operations due to transmitter harmonics. Each of these issues is addressed below.

4.2.1: Antenna Design

Requirements

One of the key requirements for supporting a cost effective multi-band LTE handset design is minimizing the number of physical antennas to fit within the user device form factor-- ideally it is desirable to have a single antenna for bands below 1 GHz. This implies the use of antenna structures with a tuning approach to optimize performance for a specific band.

Primary antenna design parameters include its length and the dimensions of the ground plane in the device. The primary (external) antenna performance characteristic is its RF radiation efficiency. The antenna length is dependent on the center frequency of operation and total range of operation. Antenna size is restricted to the space available in the user device. Internal antennas are a requirement for a competitive consumer handset (smartphone) form factor.

Antenna efficiency in a specific band of operation is driven primarily by the size of the pass band and the center frequency. The pass band requirement arises since the antenna has to operate on both the uplink and the downlink. The ratio of the size of the pass band to the center frequency determines the 1 dB efficiency parameter [QUAL1]. The Operating Spectrum and its relationship with the center frequency of operation also affect antenna efficiency. Antenna is optimized for minimal reflection coefficient and impedance matching at its input and output ports, and low cross coupling between the ports.

Antenna RF efficiency, from the standpoint of maximizing received or transmit power, is typically focused on performance optimization for the uplink due to limited UE power, at the expense of downlink performance, where high LTE base station power is easier to provide and can compensate for user device inefficiencies.

Figure 3 provides a conceptual (and highly simplified) reference for the discussion of the device antenna design parameters and performance discussion.

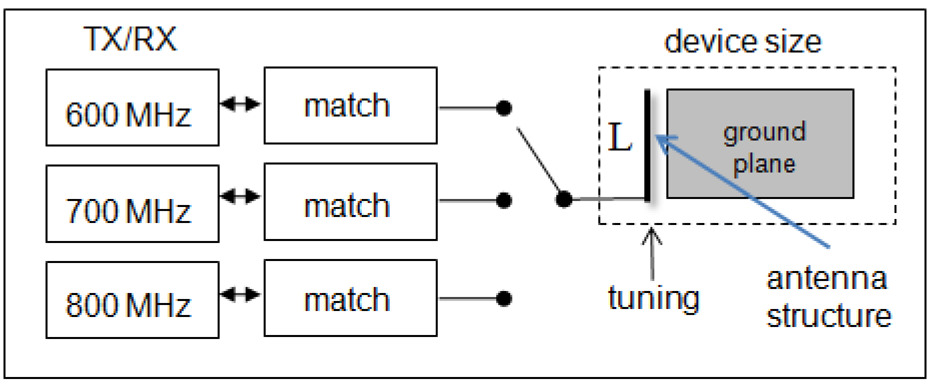

Figure 3 Reference Diagram for Device Antenna

In this diagram, the device size footprint (dashed box) is shown encompassing the antenna with length L and the associated ground plane which determine the RF performance, including frequency of operation and bandwidth. The three (potential) matching networks for three corresponding bands of operation are shown schematically, along with a potential per-band tuning approach for the antenna itself.

Antenna Size for 35x35 MHz Band Plan Using Traditional Passive Antennas

Traditional passive antenna implementations have used dipole and monopole implementations. Based on electromagnetic resonance phenomena, the half wavelength of the center frequency determines the required basic antenna length for traditional passive antennas. This corresponds to 228 mm length for the center frequency of 658 MHz associated with the 35x35 MHz band plan. Also the total range of bandwidth from 1 GHz to cover the 35x35 MHz band plan becomes 382 MHz which drives the incremental length increase and affects antenna efficiency. Table 1 provides the impact of the operation at 35x35 MHz band plan in reference to the 25x25 MHz band plan [ATT1]. [2]

Table 1: Antenna Length

	25x25 MHz	35x35 MHz	35x35 Relative to 25x25
Cntr freq (MHz)	668	658	
Operating BW (MHz)	60	80	
Basic Length (mm)	225	228	+1.3%
Total Antenna Range (MHz) (< 1 GHz)	362	382	
Addnl BW Based Antenna	1 (Ref)	1.055	+5.5%
Total "Equivalent" Increase	1	1.069	+6.9%

Using the contributions of the center frequencies and the wider band width associated with the 35x35 MHz band plan, the estimated first order increase in the length of the antenna is 6.9% as compared to the one for 25x25 MHz operation.

In case the additional length of 6.9% as compared to the 25x25 MHz cannot be accommodated and the shorter 225 mm antenna needs to be used, then the loss of receiver sensitivity is estimated to be -0.32 dB. Such a comparatively low level of detuning can be mitigated by correspondingly increasing the transmit power. Concerning transmit power, in normal operations, the User Equipment (UE) power is being adjusted dynamically. In particular, as the UE gets closer to the base station, the power is reduced. The UE's which generally transmit the maximum power of 23 dBm are near the cell edge. Hence it is possible to increase the transmit power for a significant number of the UE's.

However, most practical systems also use smaller antennas as indicated in the footnote, and hence the issues associated with use of half wavelength antennas are diffused. Alternatives including active antennas, printed antennas etc. already exist in the marketplace to handle the requirements for the 35x35 MHz band plan very effectively without loss of performance. The size of such advanced antennas is generally half of that of the traditional passive antenna.

<u>Antenna Efficiency</u>

To-date, since the lowest frequency of LTE operation has been in the 700 MHz band, it becomes desirable to provide commonality for operation with a 700 MHz design. 700 MHz antenna design

[2] In an actual smartphone design, the antenna length will be scaled (down) in order to meet the requirement for an internal antenna and the associated ground plane, and a tuning network may be introduced to optimize performance at the specific bands of operation. For example, a 5 inch long smartphone may only be able to accommodate an antenna of length 60 mm. The relative comparisons in the table would still be valid for the actual (scaled) antenna.

provides a reference point for the performance of a 600 MHz antenna. The various tuning options and the applicability of antennas for 700 MHz and 600 MHz operations are summarized in Table 2:

Table 2: Antenna Tuning Options

	700 MHz Band	35x35 MHz Band	Comments
Pass Band Tuning (1 db Efficiency) requirement	6%	5.3%	(pass band/Center Frequency)
700 MHz tuned to 6% Used for 600 MHz Operations	6%	4.6%	Detuned for 600 MHz Operation
Re-Tune 700 MHz Antenna for 600 MHz Operation	(Support 6.9%)	Meet 5.3% Requirement	Common Antenna with 700 MHz with Active Tuning
New Antenna to Support 600 MHz Operations	6%	5.3%	Common Advanced Antenna with 700 MHz

As indicated in [QUAL1], a 700 MHz antenna with a center frequency of 710 MHz is tuned and optimized for 6%, 1 dB efficiency [3]. The antenna efficiency decreases as $1/f^3$ where f is the center frequency. If the same physical antenna is used for the 35x35 MHz operation, the resulting detuning (less efficient operation) results in 1 dB efficiency of 4.6% as compared to the 5.3% requirement for the 35x35 MHz band plan [QUAL1]. The estimated detuned impact of using a 700 MHz tuned antenna for the 35x35 MHz band plan is -0.60dB. Such detuning at 600 MHz can be overcome by using active components for tuning [MAKI]. Another approach is to retune the 700 MHz antenna to a 6.9%, 1 dB efficiency for 700 MHz band operation so that the same tuned antenna can be used for the 35x35 MHz operation. This would be consistent with the desire to reuse the 700 MHz antenna for 600 MHz operation. A third option is to use an antenna with the increased length for 600 MHz operation and tune it to the 5.3% requirement for the 35x35 MHz band plan. A single antenna is acceptable for all frequency bands so long as all the antennas can be arranged within the same space of the physical limitation of the lowest resonant antenna [SONG].

The above analysis shows that using traditional dipole antennas (or scaled antennas) even if tuned to the 700 MHz band, when used for 600 MHz bands will have marginal external performance degradation. Concerning the feasibility of supporting the operating spectrum of 80 MHz, current designs can already support 65 MHz [VERI] and it is expected that by the end 2014 / early 2015 timeframe, antennas supporting operating spectrum of 80 MHz will be available based on the discussion in the next section. This is consistent with the requirement for the 35x35 MHz band plan.

Technology Feasibility of New Antennas for 35x35 MHz Band Plan

Many recent technology advances have made it possible to address the performance limitations and size issues associated with traditional passive antennas by utilizing microstrip and active antenna technologies [GUHA], [SHMB]. These have been designed with the objectives of covering a range of technologies which include LTE band plans along with the existing 2G systems, 3G systems, and Wi-

[3] This implies that the filter roll-off of -1dB from the center maximum will correspond to a bandwidth of 42.6 MHz (6% of 710 MHz).

Fi and Near Field Communication systems [MOBI]. In addition to broadband antennas covering the LTE bands, a front-end chip set to support the wide LTE spectrum range has also been announced recently [QUAL2]. Antennas for multi mode, multi frequency, and other non-cellular technologies are based on several advances which include isolated Mode Antenna Technology (iMAT) [SKYC], surface mounted band switching and active impedance matching [SHMB], printed loop antennas [WONG], ceramic substrates [MAKI], and helical antennas [EGOR], among others. These antennas are also being designed to support Carrier Aggregation (CA) and MIMO systems. The primary focus of the antennas designed to date has been to accommodate the recent 700 MHz band plans; however, the same techniques can be extended further to accommodate the proposed 600 MHz plan. For example, a surface mounted antenna covers the 690MHz to 2.7 GHz and is only 3 inches in size [MOBI]. Some of the recent implementations and their possible applicability to the 600 MHz band usage are described below.

A tunable antenna [SKYC] is based on the isolated Mode Antenna Technology (iMAT) and uses less than half the volume of traditional antennas. This enables a single and compact antenna structure that can operate on up to 12 transmit and receive bands along with MIMO technology. Another effective approach uses band switching and active impedance matching. Such antennas have already been introduced in commercial devices [SHMB]. This approach supports 13 bands and enables a smaller, more resonant antenna, providing dynamic tuning across a wide frequency range. Band switching enables the antenna to be half the size of traditional antenna to fit in the thinnest smartphone devices. In addition, innovations leveraging active impedance matching are expected to continue to be developed, which will allow the antenna to be matched dynamically and also enable quick adjustment for re-matching the antenna across wide bandwidths.

In order to reduce the size of the antenna assembly for small user devices, a compact integrated dual port antenna has been reported [RAO]. This merges two inverted F Shaped Antennas (PIFAs) into a single antenna structure and such an antenna has already been introduced in commercial products [RAO].

For LTE operations in the wide range of spectrum from 700 MHz to 2690 MHz, use of a small sized printed loop antenna with two strip monopoles for multi band operations has been proposed [WONG]. An enhancement to this approach using a folded loop with a capacitively coupled feed covers the spectrum below 1 GHz in a compact size of 60x10x6.5 mm [CHIU].

The primary issue in planar antennas as compared to dipoles is their interaction with the device ground plane. One standard mitigation approach is the physical separation of the planar antenna from the ground plane inside the user device.

These techniques illustrate how wideband operation at 600 MHz can be supported effectively based on currently available, advanced commercial products within the smaller dimensions required for a smartphone.

Supplementary Downlink and its Impact on Antenna

It is further noted that Supplementary Downlink (SDL) spectrum is being actively considered for all band plans. The primary technique for using SDL is expected to be carrier aggregation. Independent of the initial size of the band plan, whether 25x25 MHz or 35x35 MHz, it becomes necessary to expand the antenna length to handle the expanded operating spectrum range which includes the additional SDL spectrum, or otherwise accommodate the performance degradation that accompanies the wider bandwidth of operation. In essence, very similar impact occurs on the antenna length and efficiency *regardless* of which core band plan (35x35 MHz or 25x25 MHz) is chosen. Since all band plans augmented with SDL use essentially similar overall operating spectrum range, they will all require use of the same antenna subject to the accommodation of the pass band differences. In case a range of 120 MHz total operating range is assigned including uplink, duplex gap, and the paired and unpaired downlinks, then *regardless* of the band plan chosen, the operating bandwidth becomes approximately 18% of the center frequency.

For efficient operations, a common transmit antenna may be used for both the narrower 700 MHz and 600 MHz uplink operations. On the receive side, a separate tuned antenna for the 600 MHz operation may be used to accommodate increased bandwidth due to SDL and to improve downlink efficiency.

4.2.2: Duplex Filter Design

In a user device (handset or smartphone) the RF duplex filter is the component in the path between the transmitter or receiver amplifier and the antenna. (see Figure 4)

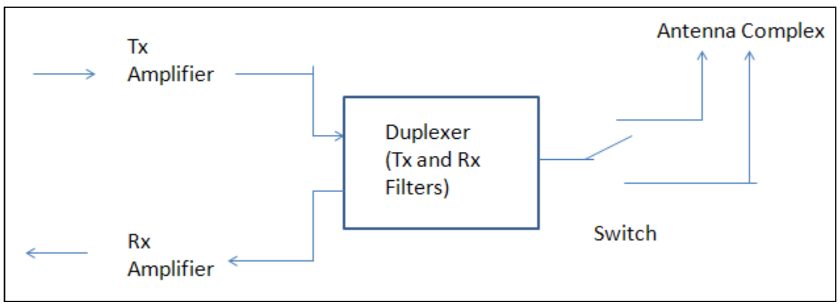

Figure 4: Duplex Filter

It prevents the relatively higher RF power produced by the device transmitter (TX) from entering the device receiver (RX) which operates at much lower receive power levels . The primary technologies currently used for cellular operations are the Surface Acoustic Wave (SAW) and the Film Bulk Acoustic Resonator (FBAR) technologies [ALU]. Similar to the Antenna tuning issue, filter implementations are driven by the ratio of the pass band to the center frequency of operations. The current state of the art allows the ratio to be in 4% range [QUAL1]. Note that the corresponding figure for Band 3 AWS is 4.2% [3GPP]. This implies the currently supported pass band to be 28 MHz for the 600 MHz operations and it is estimated that technologies in the end 2014/early 2015 timeframe will support a pass band of 30 MHz [ALU], [QUAL1].

In case filter design limitations will not support the proposed pass band of 35 MHz with 10 MHz duplex gap separation, a commonly used approach [ALU], [QUAL1] is to split the pass band into two regions and use two filters to support the segments of the overall 35 MHz. The segmentation should be done on a 5 MHz block boundary in the uplink and downlink. A representative segmentation is shown in Figure 5.

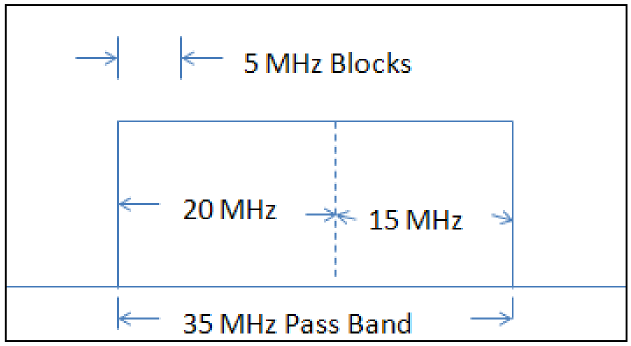

Figure 5: Filter Segmentation Illustration

Segmenting the pass band into two filter segments may also have some advantages in certain situations where there is interference, e.g., due to TV operations, in part of the total range. Use of two filters provides some protection from interference due to operations in the other segment, protection that a single filter may not be able to provide.

A practical implementation of a segmented filter may require two filters covering 2/3rd of the overall bandwidth with overlap [VERI]. Each of these filters may have 25 MHz bandwidth and the overlap between them provides good characteristics for channels of up to 20 MHz size (see Figure 6).

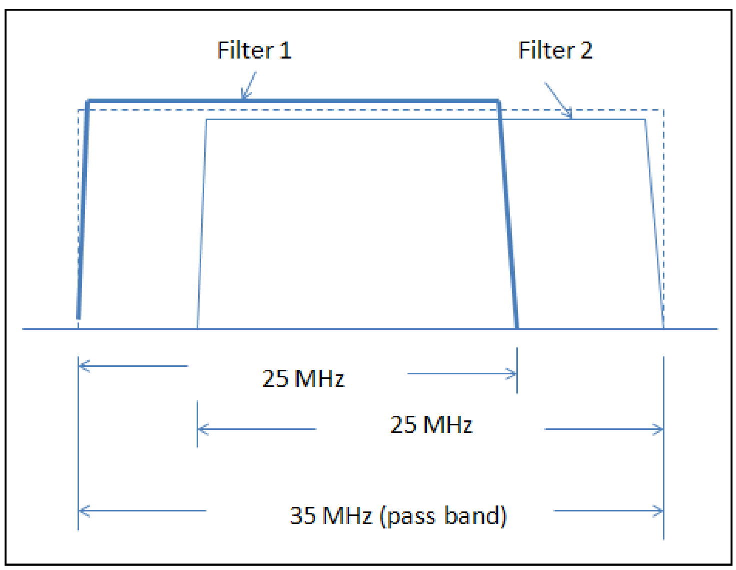

Figure 6: Two 25 MHz Overlapping Filters

The filters require associated switches, but the rest of the hardware including amplifiers and antenna can be common. New technologies like silicon on sapphire for switch paths and digital capacitors and tunable filter banks [MAKI] result in manageable additional cost and space impact to accommodate the two filters. The filters can be tuned and configured via software. A typical size of a single filter is 8 mm^3 [EPCO]. Having a second filter along with additional "glue" (interconnection) hardware may result in total size of 20 mm^3 which is relatively insignificant compared to the size of a typical user device. A compact dual filter packaging has already been shown to offer space and cost savings [MAKI].

As technology advances enable the availability of a single efficient filter in the 2015 timeframe, the two filters can be replaced by a single filter. Continued advances in both SAW and FBAR are being done especially in packaging [MAKI}. Adaptive matching using tunable capacitors will allow multiple bands to be handled with significant power savings [MAKI]]. Hence a very effective migration path exists from the two filter interim implementation to more optimal (smaller and lower cost) single filter implementation as technology evolves.

The two filter interim solution has major advantages as compared to the two band approach considered in some of the proposals to address the issue of a wide pass band. A single band approach with two internal filters proposed here provides economy of scale, more efficient interoperability, common antenna design, less network management requirements, and a migration path which leverages technology advances.

It may be worthwhile to mention here that a wider FDD based 45x45 MHz band plan formulated in 2010 has already been proposed for harmonized operations in the 698-806 MHz spectrum for the Asia-Pacific region [APT]. Similar to the 35x35 MHz band plan under consideration here, it uses dual-duplexer filter arrangement to facilitate mobile user device implementation with the overlap to provide flexibility to administrations in their national spectrum planning. The proposed duplex gap is also 10 MHz with the key parameters as 6.0% (pass band / center frequency) and 13.2 % (operating spectrum / center frequency). These are more aggressive than the corresponding ones for the 35x35 MHz band, i.e., 5.3% and 12% respectively.

Consistent with the discussion in Section 4.2.1 on the implications of using Supplementary Downlink with *any* band plan, the addition of SDL will require antennas and filters to be extended to support operating spectrum frequency of approx 120 MHz down from 698 MHz. Hence the antenna and filter advances in areas of active tuning, surface mounted and PCB implementations etc. will clearly facilitate the resolution of the antenna and filter issues relating to the 35x35 MHz band plan.

4.2.3: Harmonic Interference

4.2.3.1 Background

All RF transmitter amplifiers used in wireless devices (smartphones) generate undesired signals due to non-ideal (non-linear) transmitter operation in the uplink. It has been shown that harmonics generated from base station emissions are manageable [ALU]. Sound design will always minimize the unintended emissions from user devices that are generated along with the desired transmit signal. The undesired signals are created at harmonics (integer multiples) of the desired signal frequency [GHAR]. The undesired harmonic signals are created at power levels that are significantly lower than the power level of the desired signal, and decrease rapidly as the harmonic (multiple of the desired frequency) increases. These depend strongly on the non-linearities of the amplifiers and other elements. Typical values for the relative harmonic power levels due to such non-linearities are plotted in Figure 7.

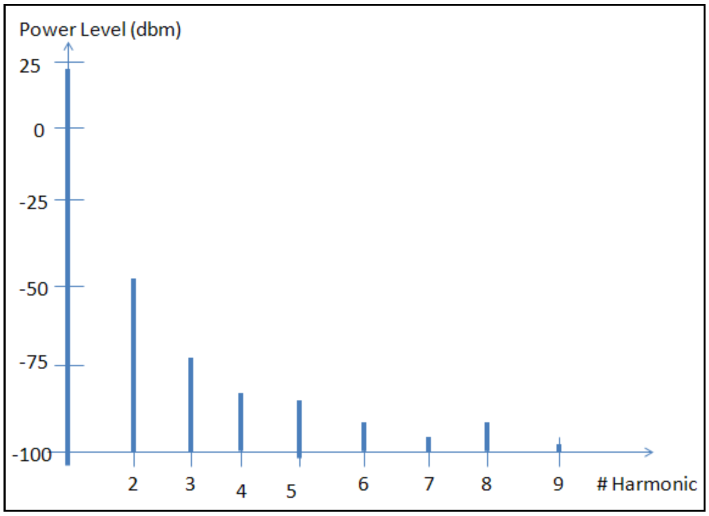

Figure 7: Illustrative Power Levels of Transmitter Harmonics

With a typical maximum value of 23.5 dBm for the desired transmitted signal for an LTE user device, the power levels of the second and third harmonics (frequency multiples) are approximately at -48 dBm and -70 dBm respectively, at the device output. The 4th and 5th harmonics are in the -80 dBm range, and subsequent harmonics are in the -85dBm to -100 dBm levels.

For the 35x35 MHz band under consideration, the affected spectrum pertaining to the various harmonic frequencies is indicated in Table 3.

Table 3: Harmonics for the 663-698 MHz Uplink Transmission

Harmonic	Frequency range (MHz)		Harmonic	Frequency range (MHz)
1st	663-698		6th	3978-4188
2nd	1326-1396		7th	4641-4886
3rd	1989-2094		8th	5304-5584
4th	2652-2792		9th	5967-6282
5th	3315-3490			

Harmonic *interference* can occur when the undesired harmonic output of user device at the higher frequency leaks over to the same user device, or another device in close proximity, which is receiving at the higher frequency *simultaneously on the downlink*. In addition to degrading the performance (throughput) of the second device, this interference may also impair the advantages of carrier aggregation.

4.2.3.2 Analysis of Harmonic Interference

The second harmonic of the 35x35 MHz band plan uplink occurs in a spectrum region which does not have active operations, and hence its impact need not be considered.

The third harmonic created by the 2 MHz frequency range 663-665 MHz in the uplink lies in a 1 MHz overlap region common to both the PCS Band 2 and Band 25 (1989 – 1990 MHz). The third harmonic may also affect an additional 5 MHz in the PCS Band 25 (1990 – 1995 MHz) as shown in Figure 8.

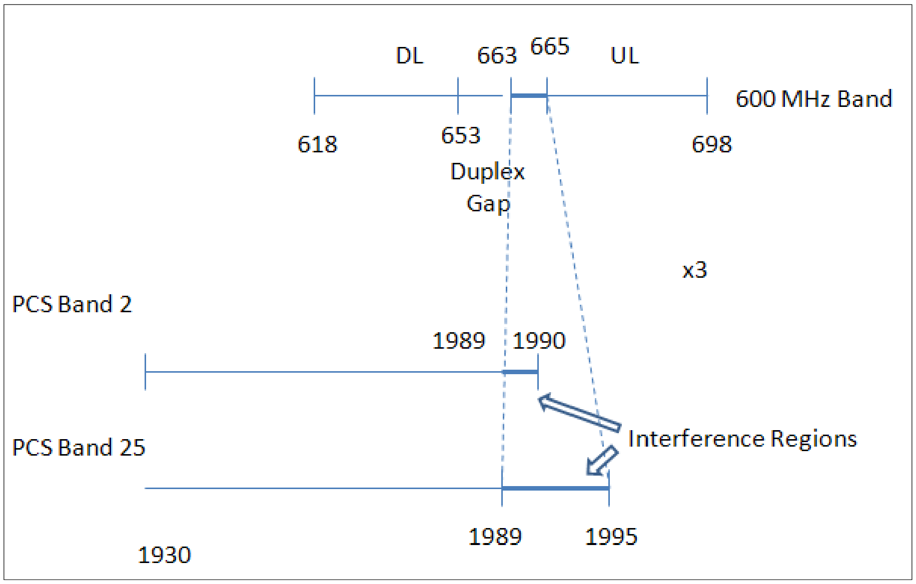

Figure 8: Harmonic Interference into the PCS Band

It is estimated that at its maximum power output of 200 mW (23 dBm), a 600 MHz device (uplink) transmitter in the user device will inject -26 dBm in a PCS receiver in a nearby device [ALU]. Assuming some level of reasonable mitigation and based on the results from the corresponding scenario between 700 MHz operation and its third harmonic interference into the AWS band [ATT1], this is estimated to create an, approximately 7 dB reduction in the PCS antenna or correspondingly, in receiver sensitivity. Typically, in communication systems, a 3dB signal loss may correspond to loss of 1 bit/symbol. For LTE using a symbol size of 6 bits for 64 QAM operation, this maps into throughput loss of 40% over the frequency spectrum affected. This is a worst case condition, as the typical output power of a user device may be much lower than 200 mW.

It is also noted that power in the 663-665 MHz segment causing the interference is shaped (reduced) according to the standard 5 MHz LTE block which has 4.5 MHz operating band with 0.25 MHz as internal guard bands on both sides [3GPP]. Consequently, the interference caused in the PCS band is further reduced (see Figure 9).

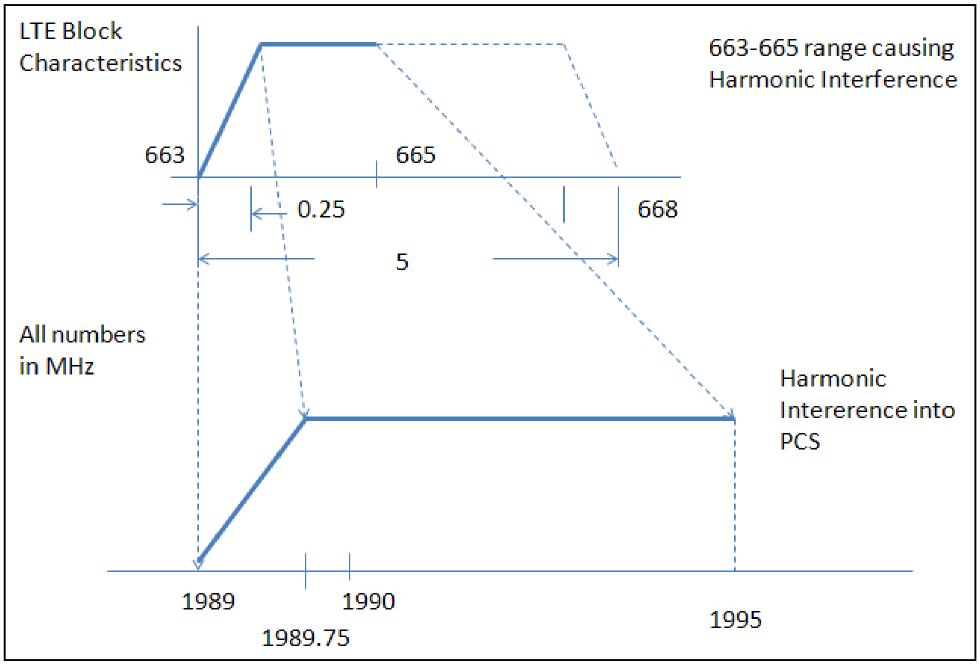

Figure 9: Third Harmonic Interference Due to LTE Block Characteristics

For the PCS band 25, this implies a capacity loss of 3.5% and correspondingly 0.42% for the PCS Band 2. These are relatively low levels of loss, again calculated at worst case power output levels and can be mitigated as indicated below Additionally, this type of interference will occur only when devices which are transmitting in the 600 MHz band, are also *simultaneously* receiving in the PCS band, or in close proximity to a device receiving in the PCS band.

It is also important to observe that the adverse effect of capacity loss for users can be curtailed by ensuring that dropped calls are minimized, as is currently done in cellular systems. Preference is given to existing sessions instead of allowing new sessions to come in. This is part of considering existing calls to be at a higher priority than new calls as part of the Key Performance Indicator (KPI) management. Hence generally, unless extensive additional interference occurs as a mobile user moves, reduced capacity will not manifest itself as dropped calls.

The relatively low levels of capacity loss estimated at worst case conditions due to harmonic interference can be further reduced or eliminated with sound engineering. Options for hardware solution include making the amplifier more linear, creating better isolation between the 600 MHz transmitter and the PCS receiver components, using different linear polarization orientations for the two antennas, or adding a harmonic filter to suppress the 3rd harmonic. A Harmonic rejection patch antenna has also been proposed for suppressing 2nd and 3rd harmonics very effectively [BINM]. A nominal isolation level of 7 dB based on use of the harmonic filter and the harmonic rejection antenna can negate harmonic interference, Patch antennas based on printed circuit technology are very compact with low cost and high reliability. Examples of use of multi pole elliptical filters to suppress higher levels of harmonics have also been reported [AGIL]. These solutions are expected to have manageable impact on space and power requirements in the user device. Additional mitigation could involve coordination or exchange of spectrum between operators with AWS and PCS holdings [NSN].

Typical criteria for severity of harmonics have been proposed in [QUAL1]. It is indicated that a harmonic level below -80 dBm may be considered to be of low severity. As seen from Figure 7, the levels for 4th and higher levels are generally in the -80 dBm or below. Hence their impact can be neglected (see also [ALU].

In particular, the 4th harmonic of the 35x35 MHz uplink band plan may potentially interfere with the Educational Broadband Service/Broadband Radio Service (EBS/BRS) band, but its effect is reduced an additional 10 dB as compared to the 3rd harmonic, resulting in a signal level below the typical sensitivity of -100 dBm [ALU], [3GPP]. Therefore, this is not expected to compromise international harmonization where the BRS band is being deployed. If necessary, mitigation approaches similar to the ones mentioned above can be applied.

It may be noted that it is not sufficient that the appropriate harmonic of an operating uplink spectrum fall in the downlink range of a potential victim to cause interference but the interference level should be sufficient to cause measureable adverse impact on the potential victim.

4.3: Issues Common to All Major Proposed Band Plans

The key technical issues which have been determined to be in common for all the major band plan proposals for the 600 MHz spectrum, including the 35x35 MHz band plan, are described in this section, along with technical approaches or solutions for mitigating adverse performance effects.

The key issues include the following:

- The size of the Duplex Gap (DG) and the types of applications allowed in the that gap
- Interference due to TV operations in the uplink domain or adjacent to downlink lower edge in a geographically overlapped region. It may be noted that one of the fundamental principles is that TV operation is not allowed in the downlink region itself.
- The Guard Band (GB) to protect the cellular operation from the TV operation and vice versa, for operations in adjacent spectrum in an geographically overlapped region
- Interference due to TV operation in the same channel in geographically adjoining and national boundary regions
- Interference due to TV operation in an adjacent channel in geographically adjoining and national boundary regions

The following sub-sections provide the framework, the impact, and the mitigation approaches for these issues applicable to all of the band plans.

4.3.1: Duplex Gap

For Frequency Division Duplex (FDD) operation, a Duplex Gap is required to isolate the uplink (UL) spectrum from the downlink (DL) spectrum. For practical systems, there needs to be a gap between the uplink and the downlink band for a filter to be able to provide isolation between the device (handset or smartphone) transmitter and receiver. Experience has shown that a duplex gap of approximately 1.5% of the center frequency [ALU] allows for a practical duplex filter design. In the case of the 35x35 MHz band plan with a center frequency of 658 MHz, this experience implies a minimum duplex gap of 9.9 MHz. Hence for the various band plans, the range of 10 – 14 MHz is recommended [QUAL1]. It may noted that there is tradeoff between increasing the size of the duplex gap for ease of filter design and decreasing it in order to improve the spectrum usage efficiency, since the duplex gap represents spectrum unusable to the wireless system.

The size of duplex gap in current 3GPP band plans varies from 13 MHz (1.8% of center frequency) to 355 MHz (18.4% of center frequency) [3GPP]. It may be noted that in many LTE band plans, the duplex gap may be created by locating other LTE band plans in the intervening space or using the duplex gap for Supplementary Downlink (SDL) and other non-interfering applications. For the situations like the 600 MHz spectrum with uplink and downlink pass bands "next" to each other, it is appropriate to use the reasonable duplex gap size of 10 MHz. This is also consistent with international harmonization efforts.

If the Duplex gap size is of relatively narrow bandwidth, the impact of the duplex gap size on the antenna is minimal if the gap is contiguous with the downlink and uplink, and it is also roughly independent of the width of the uplink or downlink pass band. The increase in the overall bandwidth resulting from a much wider duplex gap has a corresponding impact on Antenna size, as it increases the required operating range of the antenna. It is also important that the duplex gap be aligned for all operators for nationwide deployment, enabling use of a single device filter and low cost user device design.

In order to recover the spectrum usage efficiency in the presence of the duplex gap, non-interfering networks may operate within it. It is critical that the application in the duplex gap not interfere with the uplink and downlink operations. The duplex gap may be used for applications like (low power) wireless microphones [QUAL1] or for LTE Supplementary Downlink (SDL). The SDL would be used as a supplemental downlink frequency for uplink bands *other* than the upper 600 MHz uplink under consideration here.

Use of Guard Band for Broadcast TV Operation
In case the use of the duplex gap is being considered for TV operation, then corresponding guard bands needs to be placed on both sides of the 6 MHz TV band after appropriate alignment with the uplink and downlink boundaries to minimize interference. This implies total of 26 MHz guard band between the uplink and downlink with 20 MHz of the spectrum being lost. Hence insertion of TV operations in the duplex gap is not recommended. Reducing the size of the guard band would cause a TV-to-broadband wireless interference potential.

4.3.2: Interference due to Broadcast TV Operations

The interference between the TV transmission and the proposed cellular operations in the 600 MHz bands can manifest itself in the following three major ways:

1. Inter-Modulation Interference (IMI)
2. Co-Channel Interference (CCI)
3. Adjacent Channel Interference (ACI)

Interference depends upon several factors including the TV and cellular base station power, distance and distribution of the LTE user devices and the base stations, the TV transmitter and receiver distributions, signal sensitivities of the user device and the TV receiver, geographical overlaps and / or adjoining placements, propagation path characteristics, and the TV and LTE antenna and filter characteristics etc. Hence interference and its impact is complex to analyze and model and the results can vary significantly depending upon assumptions and variability in various parameters mentioned above. In this study, rough estimates of the impact of interference are derived based on measurement reports, high level modeling, and use of extrapolations and interpolations. It may also be worthwhile to mention that whereas an attempt is made in this study to segment the various interference scenarios into distinct combinations of spectrum adjacency and geographical co-location and separation, these are not necessarily mutually exclusive. In practical systems, the real interference is likely to be weighted combinations of these. The primary intent is to capture the expected impact on performance and identify possible mitigations. In actual implementations, the impact and the mitigations may need to be re-evaluated.

Typically, the moderate power TV broadcasts can be in the 50 KW range and the high powered ones in the 1 MW range. TV transmitter coverage may extend to large metropolitan areas. Base stations transmitted power may range from 50 W to 1 KW and the base stations may typically be located ¼ to 4 miles apart. The 3GPP standards specify the cell phone transmit power to be between -40 dBm and 23 dBm (200 mW) [3GPP]. Based on the distances between base stations, the received signal strength at a user device may be in the range of -30 to -80 dBm [QUAL2].

<u>Inter-Modulation Interference</u>

Inter-Modulation Interference (IMI) arises when the TV signal interacts with the uplink frequency signal from a user device and creates inter-modulation products. The interference occurs at sums and differences and multiples of those sums and differences of the two interacting frequencies. These inter-modulation products create possible interference in the receiving downlink segment of a cellular device. The initially proposed FCC band plan in the NPRM document [FCC] indicated the possibility of having TV stations in the duplex gap. Several submissions to FCC in response to the FCC NPRM document have pointed out the adverse effect of IMI in the downlink of the band plan. The currently proposed band plans, including the 35x35 MHz being considered here recommend not using TV transmission in the duplex area which could create such IMI. Hence IMI is not considered further in this study.

<u>Co-Channel and Adjacent Channel Interference</u>

Co-Channel Interference (CCI) is the result of interactions between the TV signal and the cellular signal (uplink or downlink) in the same channel. This generally creates reduced Signal to Noise Ratio (SNR) to the base station, the cell phone, or the TV receiver with resulting impact on throughput and capacity of the cellular and TV networks.

Adjacent Channel Interference (ACI) is similar to co-channel interference except for the operating frequencies of the TV operation and the cellular operation being in adjacent channels instead of being in the same channel.

The interference issues being considered here are very similar to the ones in the operation of the 700 MHz band. [SUPT]. Significant progress achieved in mitigating the interference in the 700 MHz band region is directly applicable to the 600 MHz operation.

LTE has mechanisms to handle interference and reduced signal to noise ratio by employing lower modulation levels which reduce the data rate and throughput, but maintain the desired Bit Error Rate (BER), a required part of meeting the Quality of Service (QOS) requirements in an IP system. LTE supports three levels of modulation: 64 Quadrature Amplitude Modulation (QAM), 16 QAM, and Quadrature Phase Shift Keying (QPSK). Taking the 64 QAM throughput as a reference (BW_{ref}), the corresponding throughput is typically BW_{ref} / 2 and BW_{ref} / 4 for the 16 QAM and QPSK respectively (see e.g., [GUID]). The decreased SNR may also entail packet error management mechanisms which may result in re-transmission of packets between the user device and the base station. There is hence a corresponding reduction in throughput as SNR is reduced due to interference. If SNR goes below a pre-defined threshold which does not support QPSK, then the user may need to be dropped. Such a situation results in reduced capacity. For a typical distribution of users across the whole cell coverage range, the capacity decrease may be estimated to be on the order of 1/3 of the maximum throughput.

It is expected that TV operations will be vacated from the complete downlink region above channel 37 for nationwide consistency and commonality of user devices. However, depending upon the outcome of the reverse auction, TV operations may still exist in the uplink domain in some selected regions of the country. Also, TV operations may continue in Canada and Mexico creating interference near the international boundaries. This entails the possibility of various types of interference scenarios with the cellular operations. The relationship between the type of interference and the geographic adjacency including border areas is summarized in Figure 10.

Geographic

Spectrum

		Overlapped Area	National Adjoining Area	International Border Area
Co-Channel Interference	TV & Cellular Channels		X (B)	X (B)
Adjacent Channel Interference	TV Channel / Cellular Channel	X (Guard Band) (A)	X (C)	X (C)

Figure 10: TV Co-Channel and Adjacent Channel Interference

The Interference scenarios for Uplink and Downlink are summarized in Table 4.

Table 4: TV Interference Scenarios*

Geographic	Channel	Link	Comments
Overlap	Co-Channel	DL	Not Applicable
	Co-Channel	UL	Not Applicable
	Adjacent Channel (A)*	DL (with Guard Band)	TV in Channel 36
	Adjacent Channel (A)	UL (with Guard Band)	TV in the UL spectrum pass band
Adjoining/Border	Co-Channel (B)	DL	NA for US Adjoining, Applicable for Border
	Co-Channel (B)	UL	
	Adjacent Channel (C)	DL	
	Adjacent Channel (C)	UL	

*: In reference to Figure 10

Note that overall interference may be combination of overlapped and adjoining interferences depending upon the actual geographic relationship between the TV and cellular operations. Similarly, overall interference may also need to take into account the possible combination of the channel overlap and the adjacency while calculating interference.

Geographically Overlapped Region

First consider the case of the geographically overlapped region. Clearly due to interference considerations, cellular and TV operations must not coexist in the same channels. Adjacent channel operations can, however, occur (Case A in Figure 10). The spectrum location of the TV implies two cases. The first case is the operation of the TV station operating in the uplink domain of an upper 600 MHz band plan (663-698 MHz). In this case, the cellular uplink operation is vacated from the channel(s) that the TV station is using and moved to an adjacent channel. The other case corresponds to the operation of a TV station below the lowest edge of the downlink (below 608 MHz). Both situations correspond to operation of cellular system in an adjacent channel to the TV operation.

Adjoining and Border Areas

In adjoining and border areas, TV transmission may be in the same channel as the cellular operation or in an adjacent channel. Both co-channel and adjacent channel interference are applicable. The one exception is that TV interference in the downlink channels will not occur inside the US boundary since TV operations in downlink spectrum are not planned to exist in US. However, such interference can still arise on the national boundaries with Canada and Mexico.

The interference victims for uplink and downlink signals are shown in Figure 11.

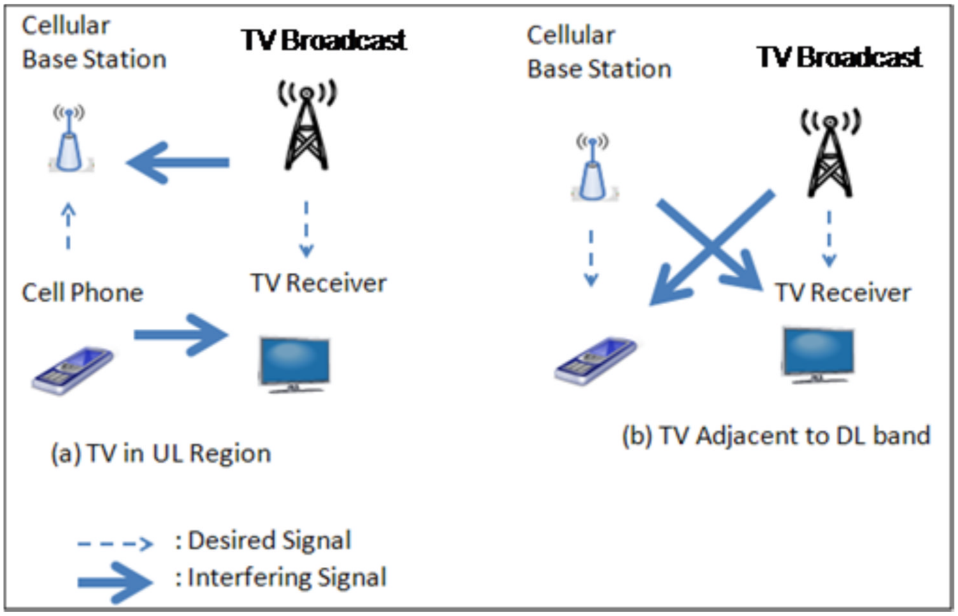

Figure 11: Targets of Potential Interference

The victim entities impacted by such interference are summarized in Table 5.

Table 5: Interference Victims

	Cell Phone	**TV Receiver**	**Cellular Base Station**
Uplink		Due to Cell Phone	Due to TV Transmitter
Downlink	Due to TV Transmitter	Due to Base Station	
Impact	Cellular Coverage/Capacity Reduction	TV Coverage Reduction	Cellular Coverage/Capacity Reduction

In the case of the TV operation being in the cellular uplink region operating in a channel adjacent to a cellular uplink block, the cellular base station and the TV receiver are the potential interference victims. The cellular base station may lose capacity. The TV receiver in the vicinity of a cellular user device may have degraded operation. This may result in coverage loss for the TV broadcast system.

It is acknowledged that it is quite difficult to predict the impact on a TV receiver due to a mobile user device [SAML].

In the case of the TV operation being in a channel adjacent to the downlink band or in the downlink spectrum, the cellular device and the TV receiver are the potential interference victims. The cellular user device may experience loss of data and dropped sessions and overall, the capacity of the cellular system may suffer. The TV receiver situation is similar to the previous case of uplink.

4.3.2.1: Geographically Overlapped Region – Adjacent Channel Interference

This situation corresponds to the Scenario A in Figure 10 where the TV and LTE networks are expected to operate in adjacent bands in the same geographically overlapped area. This necessitates the insertion of a guard band between the TV channel and the cellular band. The tradeoff for the decision on the size of the guard band is between capacity loss due to interference which decreases with increasing guard band size and overall spectrum availability which increases with decreasing guard band size.

<u>TV Operation in the Uplink Range</u>
Figure 12 shows the spectrum overlapping region between the roll-off segments of the spectrum characteristics of the TV band and the adjacent LTE band.

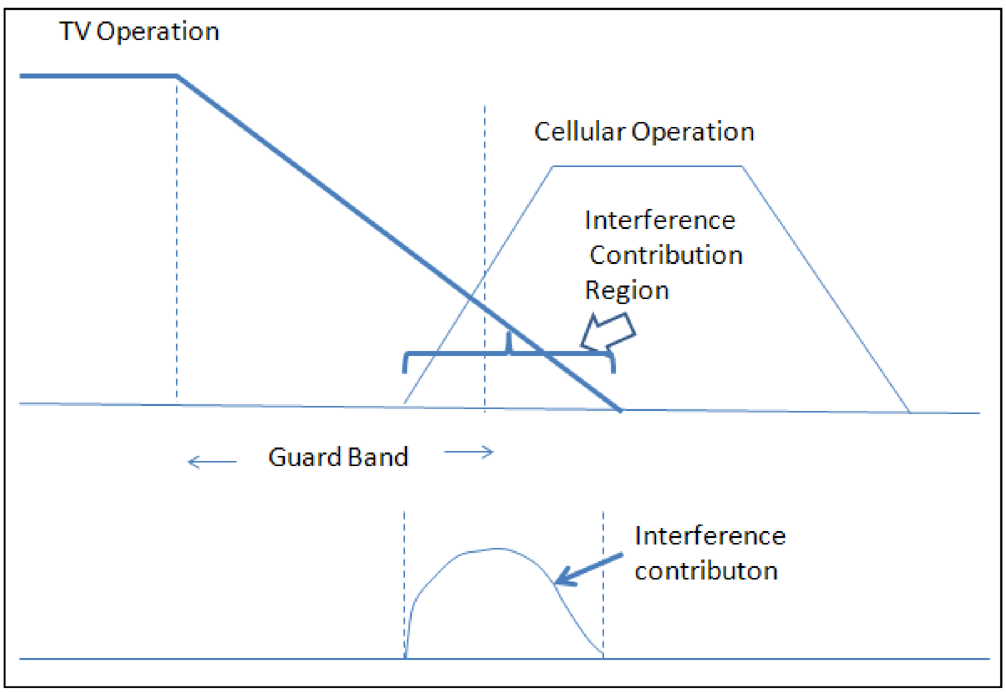

Figure 12: Guard Band for Minimizing TV Interference

For the case of the TV operation in the uplink domain and the cellular system uplink being in an adjacent block, the associated capacity loss due to interference with the base station can be mitigated using guard bands. The level of interference is clearly dependent on the size of the guard band. Several measurement studies have been carried out to capture the various interference scenarios. One prominent study [CEPT] identifies the impact on the cellular base station due to the TV broadcast in an adjacent channel. In case of no guard band, the impact can be as high as 30 – 45 dB whereas use of guard band of 10 – 20 MHz results in minimal out of band blocking level.

The interference on a typical TV receiver due to a nearby cellular uplink device in an adjacent channel without a guard band would have a TV coverage loss of 5-10% in case the cell phone and the TV receiver are in immediate vicinity [RNDH]. This can be mitigated by increasing the TV power by 0.5 dB. It may be noted that since an LTE user device is comparatively low transmit power device, the interference into a TV receiver is minimized for most practical situations when the distance is large or there are signal blocking entities, e.g., indoor / outdoor operations. In addition, significant numbers of indoor TV receivers receive their signals through cable/fiber or through satellite signals. LTE user device uplink signals will not interfere in such situations especially if the cables and other sensitive hardware are shielded. Another study estimates that there is minimal interference to the TV receiver from a cellular user device in case of an 8 MHz guard band [CHO].

Hence in case of TV operation in the uplink range, a guard band of 10 MHz is recommended with respect to the adjacent cellular band due to the impact on cellular system [ALU]. This is particularly important so as to decrease the impact due to TV operations on any of the uplink blocks. This would imply that all the blocks will essentially be "technically" equivalent. For moderate power (50 KW) TV stations, a guard band of 6 MHz is considered acceptable [ATT1]

The 10 MHz guard band in between the LTE operations and a high power TV station has also been the route the 700 MHz community has been taking as illustrated by the design of the commercial guard band filter used at the low end of the spectrum [ALU] [EPCO]. The frequency response of the commercial EPCOS filter for the 3GPP band 12 in the lower 700 MHz region to reduce interference from the TV channel 49 is reproduced in Figure 13.

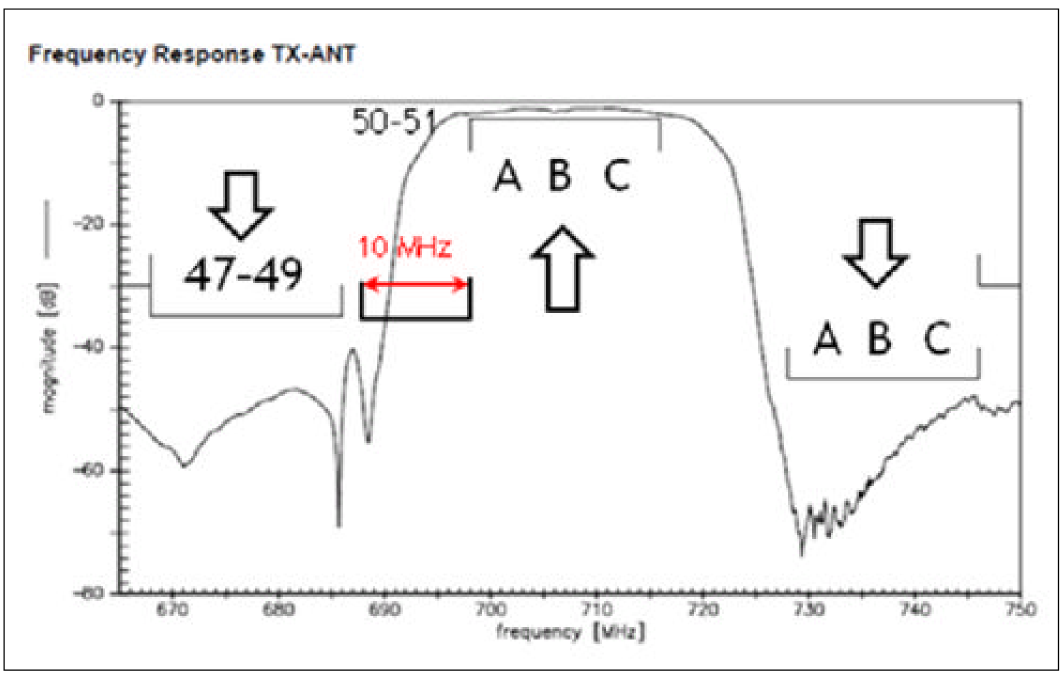

Figure 13: 10 MHz Guard Band between Band 12 and TV Channel 49 [ALU]

TV Operation near the Downlink Cell Edge

The situation of the TV operation next to the downlink of a UMTS system has also been studied previously [CEPT]. This analysis is expected to apply to LTE operations. The loss of capacity is characterized in two environments – at the annular area at the cell edge (see Figure 14), and as an average across the whole cell area.

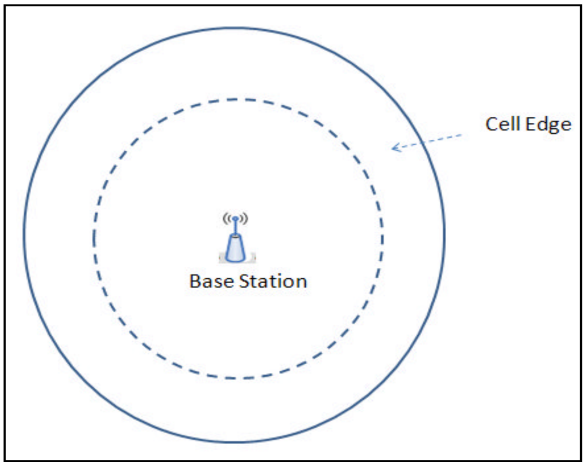

Figure 14: Cell Edge Area

The results for the cell edge capacity loss are summarized in Table 6.

Table 6: Cellular Capacity Loss near Cell Edge

Guard Band	Cellular Capacity Loss (%)
No guard band	24% (extrapolated)
3 MHz	20%
8 MHz	14%

It may be noted that when the impact of interference is averaged over the whole cell, then the capacity loss is 5% without a guard band. The corresponding impact on the TV coverage even with a 1 MHz guard band is estimated to be 3% [CLEA].

Similar to the case of the TV operation in the uplink regions, in the case of TV operation below the Downlink edge, a guard band is expected to address the interference issue. For the proposed 35x35 MHz band plan, a 10 MHz guard band is created by inserting a 4 MHz Guard band which augments existing isolation provided by the 6 MHz channel 37. Channel 37 applications operate in a non-interfering mode with the LTE bands. Thus the 35x35 MHz band plan provides a very efficient usage of the spectrum above channel 37.

In case there is a need to further reduce interference after the introduction of a guard band, or if adequate interference reduction has not occurred in specific cases, then several additional measures have been recommended [CLEA] as summarized in Table 7.

Table 7: Additional Mitigation Approaches

Unit	Mitigation	Applicability	
		TV near Cellular UL	TV near Cellular DL
TV Receiver	In Line Filter	X	X
	Signal Selectivity	X	X
TV Transmitter	On-Channel Repeaters		X
	Antenna Height		X
	Antenna Pattern and Beam Forming		x
	Co-siting (with cellular base station)		x
Cellular Base Station	Transmitter Filtering		X
	Orthogonal Polarization		X
	Power Reduction		X
	Antenna Height		X
	Antenna Pattern and Beam Forming		x

The In-line filter option for TV receivers is considered impractical because of the necessity of upgrading all affected customer TV receivers. The on-channel Repeater approach basically involves increasing the transmitted power of a TV station. This is most effective of the various solutions but also is most expensive and may also add interference to the cellular user device. Adjustments of antenna characteristics (height, pattern, tilt, and direction) [SAML] are comparatively inexpensive and are part of finer optimization. This is true for the cellular base station as well. Co-siting and directing the energy for the TV station and the cellular base station is quite effective in situations where the respective coverage areas are comparatively disjoint. Base station transmitter filtering is also very effective and may cost approximately $600 per base station [CLEA]. Orthogonal polarization may give up to 16 dB additional protection [SAML] and does not entail significant cost since it is a matter of orientation of the transmitted waves. The power reduction in the base station may be the least desirable option to reduce interference to the TV receiver since it reduces the cellular network coverage as well.

Spectrum below Channel 37

It is also envisaged that the channels directly adjacent to and downward from channel 37 may not be used for TV transmission. Major alternatives exist for useful application of that range of spectrum, e.g., use as Supplementary Downlink (SDL) for the upper 600 MHz band plan or in support of the band plans in the 700 MHz, PCS, or other LTE bands. This will facilitate the support for many multimedia applications wherein the downlink requires substantially more bandwidth than the uplink. In fact, most technologies use the strategy of expanding the downlink with additional bandwidth. Similar strategy of enhancing the downlink performance applies in the access techniques used in downlink and uplink in LTE. LTE uses OFDMA for the downlink with its enhanced performance in contrast to SC-FDMA for the uplink.

Hence in both the cases of geographically overlapped operations, whether the TV operation is in the uplink region or the downlink adjacent region, a guard band facilitates the mitigation of interference. This implies that the impact on the lowest downlink block is minimized and this makes the spectrum value of the lowest block similar to other blocks further away. Hence each block has similar propagation characteristics, similar interference features (including issues associated with interference from cross-border licensees in Canada and Mexico), and similar capabilities of communicating devices. This results in comparatively "uniform" value for the blocks in the entire spectrum range.

4.3.2.2: Geographically Overlapped Region – Guard Band

The suggested guard band values are 6 MHz and 10 MHz for the moderate power 50 KW and the high power 1 MW TV transmitters respectively [RNDH]. It may be worthwhile to note that there is no specific threshold value for the size of the guard band. The primary trade-off is between decreased interference due to increase in the size of the guard band and the corresponding reduction in throughput and capacity. A typical 6 MHz TV station in the cellular uplink region may require guard bands on both sides unless it is at the low end close to the Duplex Gap. The size of the guard band also may need to be adjusted to align with the standard 5 MHz block boundaries for the LTE operation.

A representative guard band scenario for a moderate power TV station operating in the uplink region is shown in Figure 15.

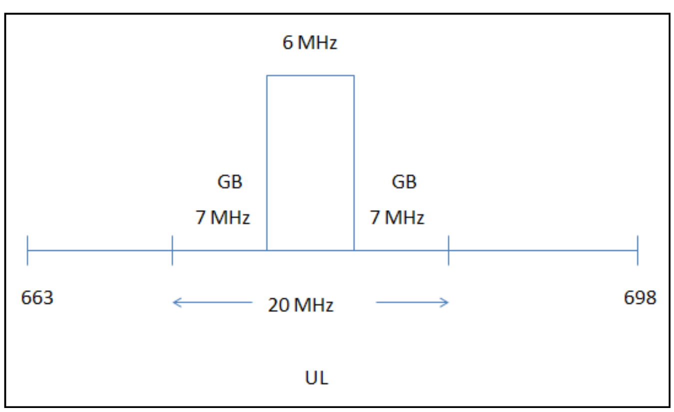

Figure 15: Moderate Power TV Operation with Guard Bands

A single moderate power TV station will result in a loss of 20 MHz of spectrum from the uplink region. As the number of TV stations increases, the corresponding adjusted guard bands may be needed between the end TV stations and the cellular operation. No guard bands are required between adjacent TV channels.

The corresponding situation for a high power 1 MW TV station is depicted in Figure 16.

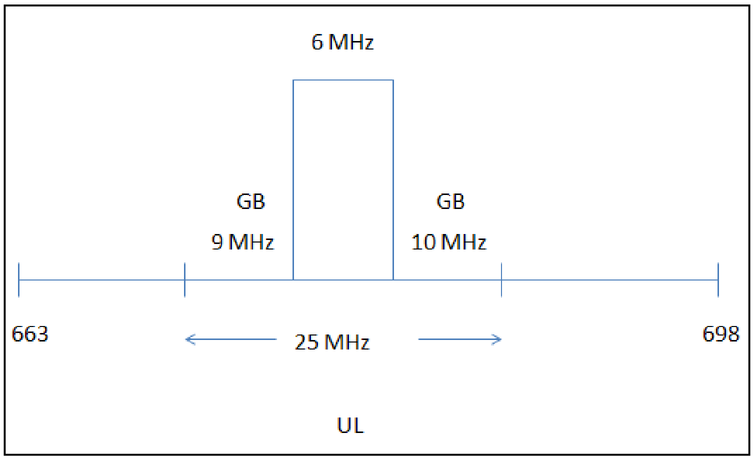

Figure 16: High Power TV Operation with Guard Bands

The reduction in the uplink region in the case of a high power 1 MW TV station is 25 MHz.

To the first order, the primary impact of a TV station is to reduce the availability of cellular uplink blocks. It may be noted that the corresponding paired downlink block also becomes non - operational resulting in a loss of 5 MHz of bandwidth for each block. It is proposed that 3GPP consider as a future work item the feasibility of using a previously paired downlink block as a Supplementary Downlink in case the corresponding uplink is not available.

It may be noted that TV operations cannot be inserted at the high end (692-698 MHz) of the uplink spectrum because of possible interference with the low 700 MHz band. However, if the TV operations in uplink start at the low end (663 MHz of the 35x35 MHz band plan), then the duplex gap effectively acts as a guard band, and only one guard band is needed at the high end of the TV operation. Such typical situations are depicted in Figures 17 and 18 for the 25x25 MHz and the 35x35 MHz band plan respectively.

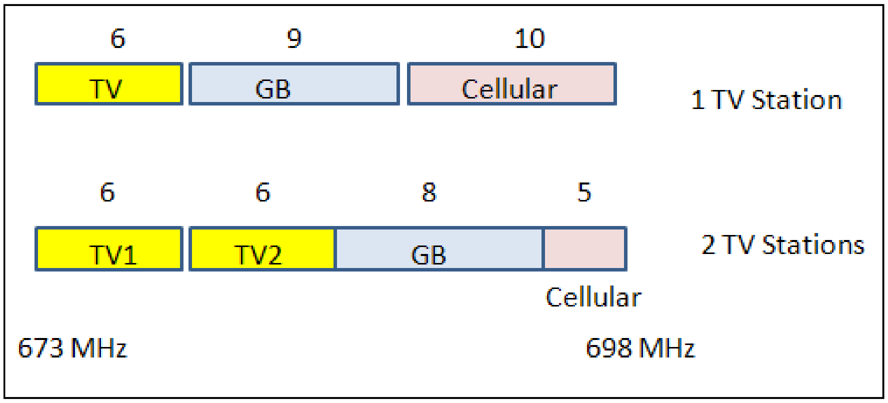

Figure 17: Illustration for TV Operations in 25x25 MHz Uplink

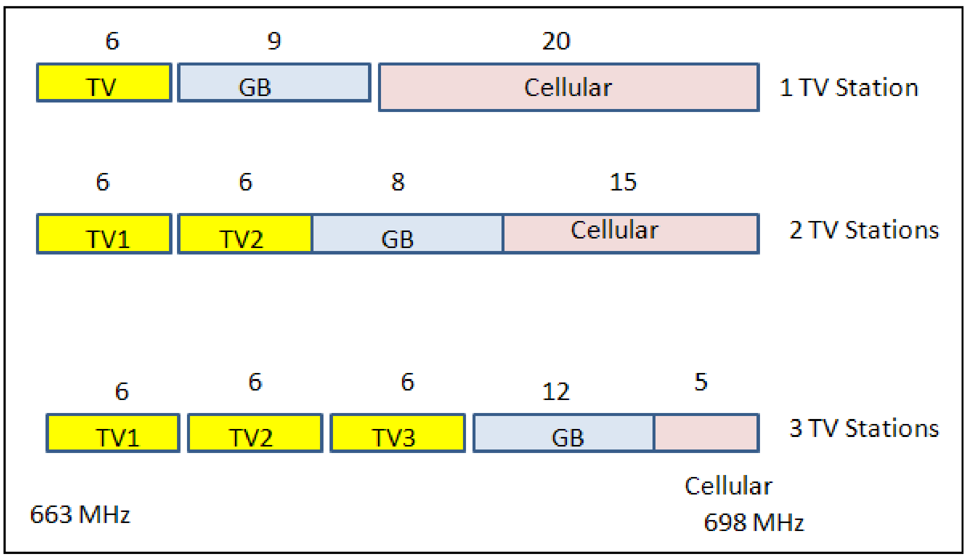

Figure 18: Illustration for TV Operations in 35x35 MHz Uplink

It may be noted that in Figures 17 and 18, nominal guard bands of 8 MHz or higher sizes are being used so that the cellular blocks can be aligned with Multiples of 5 MHz boundaries. Table 8 summarizes the loss of throughput and hence the corresponding capacity level, due to elimination of the range of blocks due to the presence of TV stations from Figure 17 and 18.

Table 8: Capacity Reduction for TV Stations in Uplink Region

# TV Stations	25x25 MHz Band Plan		35x35 MHz Band Plan	
	Available BW	% of Maximum	Available BW	% of Maximum

	(MHz)	Capacity	(MHz)	Capacity
0	25	100	35	100
1	10	40	20	57
2	5	20	15	43
3	0	0	5	14

As indicated in Table 7, there is substantial loss of throughput and capacity in case of the operation of TV station(s) in the cellular uplink region. Because of the significant nationwide value for the cellular spectrum and the focus on providing the maximum spectrum to the customers, it is recommended that TV stations be relocated from the entire uplink spectrum nationwide for any of the band plans.

4.3.2.3: Geographically Adjoining and Border Regions – Co-Channel Interference

This corresponds to the Region B in the Figure 10.

The TV station, the cellular base station, and the user device may be located at arbitrary locations as shown in Figure 19.

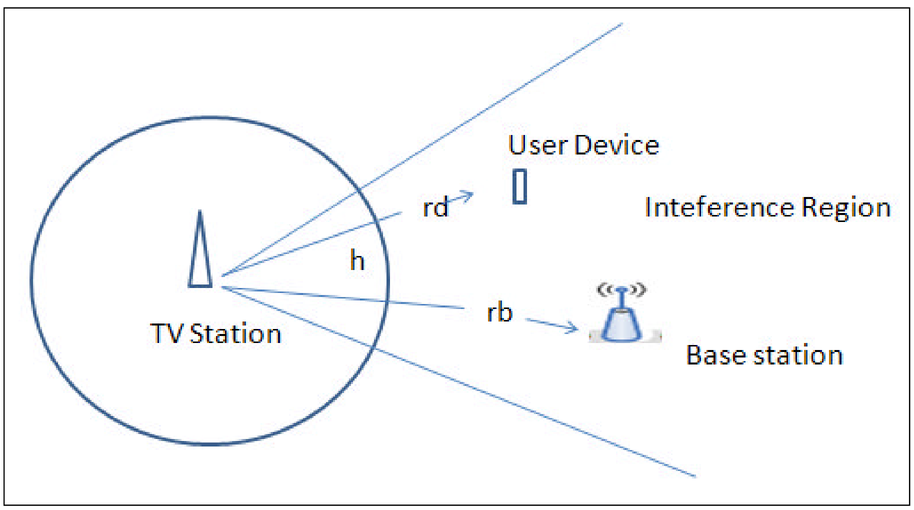

Figure 19: Geographically Adjoining Areas

As stated earlier, the identification of interference and its impact varies according to the assumptions made for the transmit power, receiver sensitivity, differing coverage areas for the TV and the cellular operations, and geographic distributions.

A geographically adjoining area implies the existence of TV station in one city or Economic Area (EA), with the cellular operations in a neighboring city or an EA. The border situation with Mexico and Canada is very similar to the one for adjoining area. A factor "h" may be used to indicate the fraction of the complete periphery relating to the adjoining interfering areas. As an initial assumption, the factor may be neglected and considered as 1.

Co-channel Interference (CCI) will clearly be applicable in geographically adjoining and border areas. CCI arises from television stations operating in neighboring cities and towns in the same spectrum range that a cellular base station is using. The TV signal interference with the uplink signals from the mobile devices will impair the base station's ability to receive the mobile signals. This also affects the performance of the TV receiver. Even if all the TV stations in the US are removed from the cellular uplink spectrum and moved to other frequency regions, the scenario can still exist in the border region.

Similarly, the interference between the TV transmission and downlink signal affects the performance of both the cellular phone and the TV receiver. This scenario is not applicable inside the US since all the TV stations are expected to vacate the downlink spectrum.

The co-channel interference depends upon the overlap between the 6 MHz band of operation for the TV station and the 5 MHz block for the cellular system as shown in Figure 20.

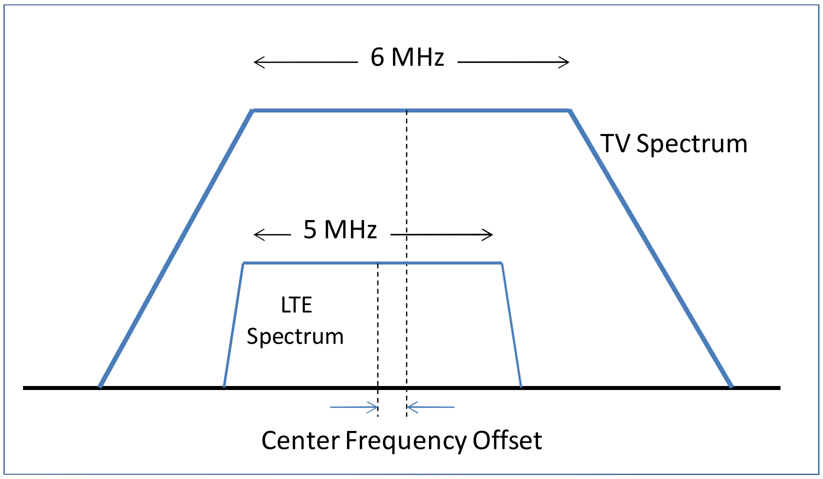

Figure 20: Co-Channel Spectrum Overlap

It is clear from Figure 20 that such interference will occur in the spectrum overlapping region and will decrease as the offset between the center frequencies of the TV station and the cellular system increases.

Extrapolating the measurements [ALU], [NSN], [CEPT] from the adjacent channel to a co-channel situation, the corresponding loss for a typical cellular system can be estimated.

For typical TV broadcast, only the side lobes interfere with cellular systems in close proximity (< 1 Km). The placement of the TV antenna at large height and pointing of the main lobe at distances of 10 – 15 Km results in interference which varies depending upon the distance between the TV station and the victim system. A typical value for such interfering signal may be -30 dBm [NSN2]. The measured signal strength due to a moderate power TV station at distances of 0.4 – 3.5 km indicated -23 dBm [ALU]. [NSN2]. The corresponding signal is -10 dBm for a high power TV transmitter using a 13 dB difference between the two. The signal is reduced further based on filter (-10 dB) and antenna (-5 dB) corrections at the receiving base station. This signal interferes with the signal received from a cellular user device. Extensive Monte-Carlo simulation results on the mutual co-channel interference have been published [GUID] with particular emphasis on interference by the TV station on the LTE base station in the uplink in the 800 MHz band. As a first order of approximation, the results are expected to be roughly applicable to the 600 MHz band region as well. Variations in several parameters have been studied including TV power and antenna patterns, TV duty cycle, base station distributions,

It may be noted that the performance degradation also depends on the modulation scheme. Using typical values from the results in [GUID], high power TV operation may result in estimated 33% capacity loss.

The variation of the capacity loss as a function of the offset between the center frequencies of the TV station and the cellular system using linear interpolation is depicted in Figure 21.

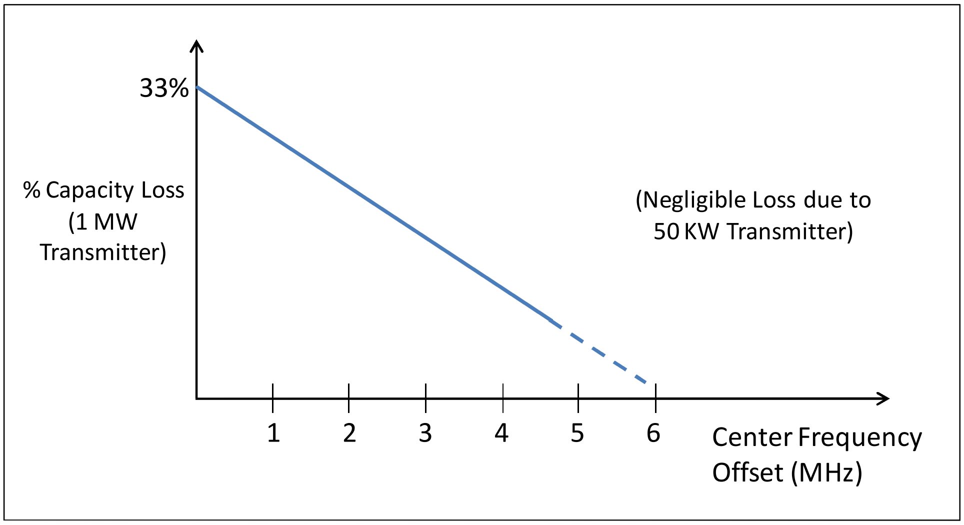

Figure 21: Capacity Loss due to Co-Channel Interference

The base station may be situated at different distances from the TV station. A first order approach to calculate the effect as a function of distance is to estimate the reduction in the interference signal strength and the corresponding reduction in the loss of capacity by noting that for free space propagation, the signal power decreases as power of two of the distance for omni-directional transmit antennas. For every doubling of distance, the power decreases by 6 dB. Hence the loss of capacity also decreases correspondingly. This is indicated in Figure 22. It may be noted that this decrease in capacity loss may need to be modulated with the actual signal strength depending upon the TV antenna pattern as indicated above.

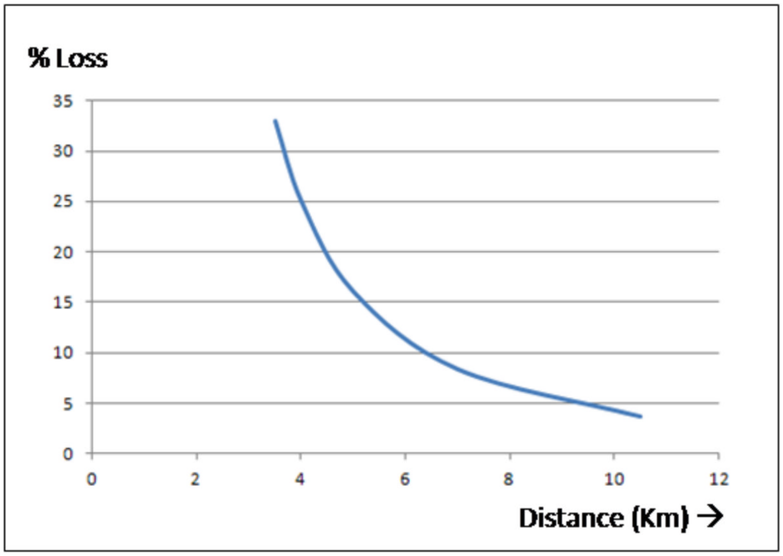

Figure 22: Capacity Loss as a Function of Distance between TV Station and Base Station

In this first order model, the ground path loss effect which depends on urban, semi-urban, or rural environments is not accounted for. If necessary, this can be done by including the corresponding path loss factor (see e.g., [HUFF]) which will reduce the capacity loss in this case correspondingly and hence interference as well.

The primary approach for reducing and eliminating Co-Channel interference is to ensure that enough incentives exist for the TV station operator to vacate the whole uplink region for the 600 MHz spectrum.

In case TV stations still exist, e.g., in the border areas, various approaches for interference mitigation or exclusion are feasible, and have been applied to 700 MHz operations [ALU]. These approaches include geographic isolation, co-siting and antenna orientation coordination, placing coordinated interferers on the same tower back to back, and use of ground level limitations of power density.

4.3.2.4: Geographically Adjoining and Boundary Regions – Adjacent Channel Interference

The remaining "C" grids in Figure 10 also correspond to the cellular operation in a band in a region which is adjoining another region with TV operations. The TV channel does overlap the cellular system as in the case of CCI but it is adjacent to the one being used by the cellular system. Such interference arises due to the TV station transmitted power falling within the cellular spectrum due to the transmit filter roll-off, and can be considered to be equivalent to a typical adjacent band scenario considered in scenario "A", but with the guard band being zero. The interference in this case is expected to be less as compared to the geographically overlapping scenario because of separation distance between the TV and the cellular coverage. As described previously, field measurements [CEPT] indicate that there is a 5% capacity loss across the cellular network due to the interference by the TV station. The further reduction in the capacity loss for adjoining and border regions will depend on the distance between the TV coverage and the cell coverage areas. Using the approach indicated in Figure 22, one can estimate that for a distance of 10 km, the loss may be as low as 1.2%.

For both the co-channel interference and the adjacent channel interface cases, there are several mitigation techniques available [CEPT] (Also see Table 6). These including co-siting the respective antennas and pointing them in the appropriate areas, use of cross-polarization between the cellular system and the TV broadcast, using selective spectrum mask, adjusting power of the base station or the TV station, adjusting the antenna heights, beam forming the antenna pattern, installing rejection filters, and more stringent out of band emission control. Guard Bands have also been suggested to further reduce interference, [CEPT] but this results in a corresponding loss of throughput and capacity. In addition unlike a mobile user device, since the cellular base station is a fixed entity, network planning is also a tool for managing interference due to base stations.

In all cases, it is undesirable to have separate market-by-market clearing targets for TV operation, with corresponding nationwide variations in the allowable spectrum for cellular operations.

4.3.2.5: Interference Impact Summary

As described in Sections 4.3.2.1 to 4.3.2.4, various combinations of geographic separation, channel separation, and link direction result in different impact in the cellular and the TV networks. A summary of these is provided in Tables 9 and 10 for geographically overlapping regions and Adjoining / Border regions.

Table 9: TV Operations in Geographically Overlapped Regions

Channel	Link	Impact		Comments
		Cellular Network	**TV Operations**	
Co-Channel	DL	NA	NA	TV and Cellular operations not allowed in same channel
Co-Channel	UL	NA	NA	
Adjacent Channel	DL (Below Lower Edge)	Manageable with Guard Band	Manageable with mitigations	GB: Ch 37 + 4 MHz
Adjacent Channel	UL	Significant Reduction in Available Bandwidth	Minimal due to cell phone except in close vicinity	10 MHz Guard Bands

Table 10: TV Operations in Geographically Adjoining and Border Area Regions

Channel	Link	Impact		Comments
		Cellular Network	**TV Operations**	
Co-Channel	DL	Major loss of Capacity	Manageable with mitigations	(Only in Border Area)
Co-Channel	UL	Manageable with Mitigation	Minimal due to cell phone except in close vicinity	
Adjacent Channel	DL	Manageable with mitigations	Manageable with mitigations	
Adjacent Channel	UL	Manageable with mitigations	Minimal due to cell phone except in close vicinity	

As Table 9 indicates, a major area of concern from a throughput and capacity viewpoint in geographically overlapped areas is allowing TV operations to exist in the uplink spectrum region (663 – 698 MHz). The cellular operations in the channels being used by the TV clearly cannot be used by cellular systems in those markets. Cellular operations then need to be assigned adjacent channels. This requires at least a 10 MHz guard band in the useful uplink spectrum area and reduces correspondingly the blocks available for cellular systems. However, other situations, including impact on TV receivers, are minimal and manageable. One set of measurements has shown that the interference due to cellular uplink on a TV receiver is minimal if the LTE user device is more than 2.5 m. away from the TV receiver [RNDH].

In the case of TV operations in one area, cellular operations may be allowed in the geographically adjoining area in the same channel as TV or in an adjacent channel (see Table 10). The co-channel scenario is not applicable for the downlink within the US since all TV operations are removed from the cellular downlink spectrum channels. However, in case of border areas, TV operations may continue in the cellular downlink spectrum area and this will have major impact on cellular operations in US border areas. The adjacent channel operations are manageable with mitigation.

It may also be noted that with the use of cable/fiber and satellite channels by TV receivers, the impact on TV reception due to interference from cellular operations is further minimized. However, TV broadcast operations in both uplink and downlink have significant impact on cellular operations. The risk of interference cannot be zero and judicious selection of mitigation techniques during implementation can result in acceptable performance for both the cellular and the TV operations [SAML].

These conclusions are applicable essentially to all the major band plans starting downward from 698 MHz. In all these cases, **t**he higher frequency pass band is used for the uplink, and the lower for downlink. These are separated by a technically feasible and minimum sized Duplex Gap as discussed in Section 4.3.1.

5.0 Conclusions

Using the core evaluation criteria, the analysis has identified the advantages as well as the technical challenges unique to the 35x35 MHz plan, compared to other plans. The primary advantage of this plan is the ability to provide additional 40% traffic capacity for users and operators as compared to a 25x25 MHz band plan. Unique challenges include handset antenna performance, duplex filter feasibility, and the potential for harmonic interference with a portion of the existing PCS band. The analysis further shows that current technology or anticipated technology improvements can overcome these challenges, and that even when these issues are taken into account, the 35x35 MHz plan provides the greatest amount of broadband wireless capacity to users and operators. In essence, instead of being limited by current technologies, the proposal exploits technological advances consistent with the 2014/2015 timeframe when the systems in the 600 MHz bands are likely to be introduced in the marketplace. These will result in more compact user devices and higher performance. This is considered as a more desirable and effective solution from a longer range viewpoint.

Resolution or mitigation of potential technical issues unique to the 35x35 MHz band plan includes:

- Device Antenna: Use of active antennas, innovative printed circuit board antennas, and other technological advances already in place in existing smartphones, or under development, optimizing current antennas for 600 MHz operations.
- Duplex Filter: Use of an overlapping duplex filter configuration in the short term until technology allows consolidation into a single filter, likely in the 2015 timeframe
- Harmonic Interference: Managing the low interference power levels and low likelihood of occurrence of potential harmonic interference into the PCS band by better isolation and harmonic filter technologies, and coordination of 600 MHz and PCS operations.

The analysis also reveals that the 35x35 MHz plan shares several technical issues in common with other proposed plans, none of which prevent successful operation or deployment. Importantly, these band plans remove technical issues inherent to the FCC proposed band plan, in particular, the spectral inefficiency resulting from operation of broadcast TV in the duplex gap and the potential for inter-modulation interference caused by high power broadcast TV operations.

The characteristics that the 35x35 band plan shares with other similar proposals can be summarized as follows:

- Uses 5 MHz paired interchangeable FDD blocks.
- Uses a 10 MHz Duplex Gap with no TV operation in the Duplex Gap.
- Allows channel 37 (608-614 MHz) to continue to be used for medical and other unlicensed applications.
- Provides a total of 10 MHz guard band for broadcast TV channels below 37 (608 MHz).
- Reinforces the use of 6 MHz guard band for moderate power (50 KW) TV transmission.
- Reinforces the consensus on re-locating TV operations from the 600 MHz downlink region.
- Allows for potential use of Supplementary Downlink (SDL) operations below the paired downlink boundary.

- Suggests relocation of the TV operations from the uplink spectrum because of substantial impact on cellular operations.
- Allows the use of common antennas for all the operations below 1 GHz, as is currently done for 700 MHz band plans.
- Exploits many of the mitigation techniques already being used in the 700 MHz band.
- Suggests extensive coordination with the TV operations in Canada and Mexico to avoid co-channel and adjacent channel interference with US cellular operations in the border areas.

The 35x35 MHz band plan proposal focuses on efficient usage of the spectrum, maximum pass band for significant value to the customers and the operators, leverages realistic technological advances, and suggests appropriate protective measures for potential interference both with other LTE systems and TV operations.

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[WONG] Wong, K and Chen, W, *Small sized Printed Loop-Type Antenna Integrated with two stacked Coupled-Fed Shorted Strip Monopoles for eight Band LTE/GSM/UMTS Operation in the mobile,* Microwave and Optical Technology Letters, Jul 2010, http://onlinelibrary.wiley.com/doi/10.1002/mop.25257/pdf

Appendix A: Other Band Plan Proposals

This section contains descriptions of other band plans that have been proposed and evaluated for application to the 600 MHz incentive auction spectrum. These descriptions are provided to facilitate comparisons to the 35x35 MHz plan made in Sections 3-6.

A.1 25x25 MHz Plan

A 25x25 MHz band plan has been proposed in [ATT1] and [QUAL1]. In the initial band plan proposed in [ATT1], a duplex gap of 14 MHz is used with spectrum, providing for two, 6 MHz TV channels above Channel 37 (see Figure A.1).

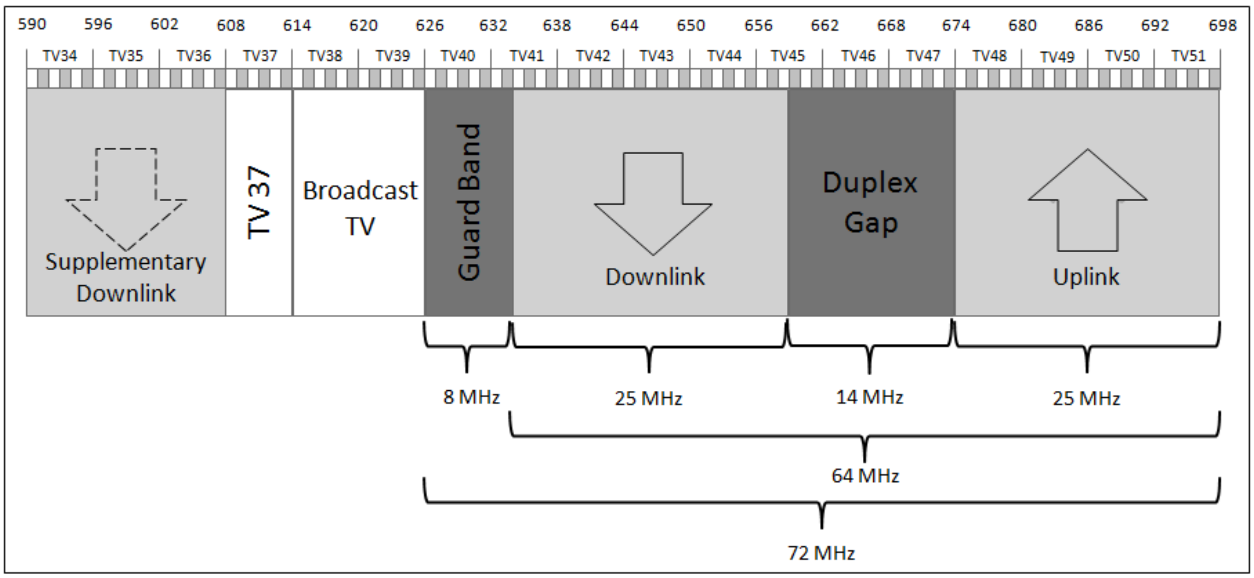

Figure A.1: A Representative 25x25 MHz Band Plan

A.2 30x30 MHz Plan

A 30x30 MHz band plan which allows for one TV station above channel 37 has also been proposed and considered by [QUAL1], [ALU],.(See Figure A.2)

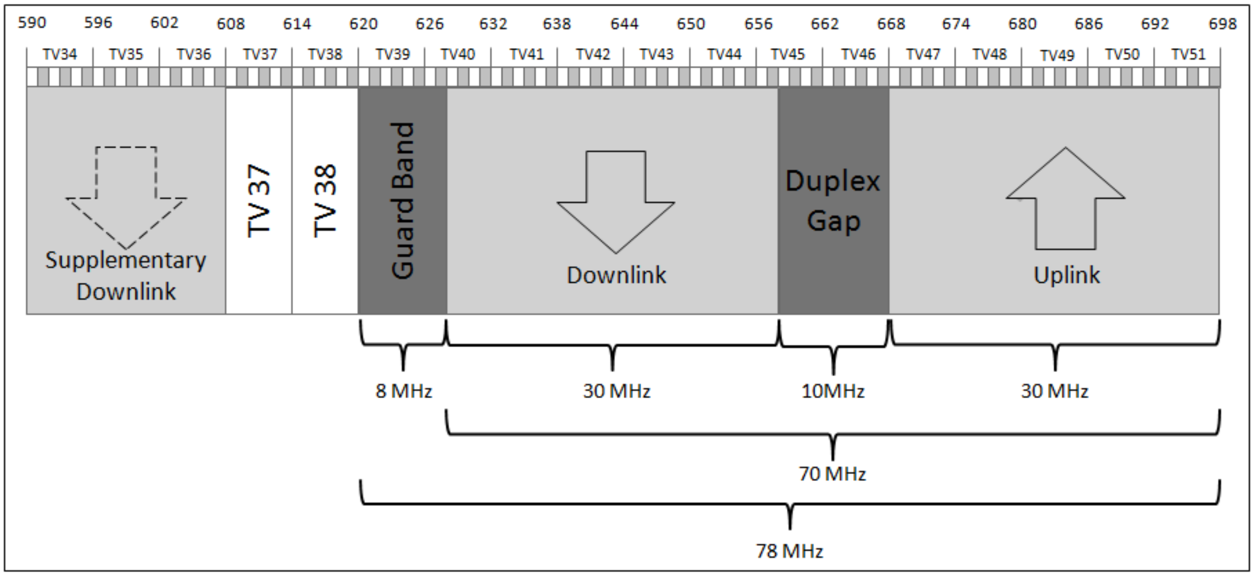

Figure A.2: A Representative 30x30 MHz Band Plan

In both the 25x25 MHz and 30x30 MHz plans, TV operation with its associated 8 MHz guard Band (GB) is not the only option for using the spectrum above channel 37 (614 MHz). It is envisioned that if sufficient broadcast TV channels can be cleared, the spectrum between 614 MHz and the lower end of the proposed downlink), which is 634 MHz and 628 MHz for the 35x35 MHz and the 30x30 MHz band plans respectively, can be used for other applications, for example, supplementary downlink (SDL), or secondary unlicensed applications.

Appendix B: Company Profile

Profile: Roberson and Associates, LLC
Roberson and Associates, LLC, is a technology and management consulting company serving government and commercial customers that provides services in the areas of RF spectrum management, RF measurements and analysis, strategy development, and technology management. The organization was founded in 2008 and is composed of a select group of individuals with corporate and academic backgrounds from Motorola, Bell Labs (AT&T, Telcordia, Lucent and Alcatel-Lucent), IBM, IITRI (now Alion), independent consulting firms, and Illinois Institute of Technology. Together the organization has over 300 years of the high technology management and technical leadership experience with a strong telecommunications focus.

Profiles: Roberson and Associates, LLC, Staff
Dennis A. Roberson, President and CEO, Roberson and Associates
Mr. Roberson is the Founder, President and CEO of Roberson and Associates, LLC. In parallel with this role he serves as Vice Provost and Research Professor in Computer Science at Illinois Institute of Technology where he has responsibility for IIT's corporate relationships including IIT's Career Management and Technology Transfer efforts. He also supports the implementation of IIT's Strategic Plan, the development of new research centers, and the successful initiation and growth of IIT related technology-based business ventures. He is an active researcher in the wireless networking arena and is a co- founder of IIT's Wireless Network and Communications Research Center (WiNCom). His specific research focus areas include dynamic spectrum access networks, spectrum occupancy measurement and spectrum management, and wireless interference and its mitigation and of which are important to the Roberson and Associates mission. He currently serves on the governing and / or advisory boards of several technology-based companies. Prior to IIT, he was EVP and CTO at Motorola and he had an extensive corporate career including major business and technology responsibilities at IBM, DEC (now part of HP), AT&T, and NCR. He is and has been involved with a wide variety of Technology, Cultural, Educational and Youth organizations currently including the FCC Technical Advisory Council and Open Internet Advisory Committee, the Commerce Spectrum Advisory Committee, and the National Advisory Board for the Boy Scouts of America and its Information Delivery Committee, and the Board of HCJB Global. He is a frequent speaker at universities, companies, technical workshops, and conferences around the globe. Mr. Roberson has BS degrees in Electrical Engineering and in Physics from Washington State University and a MSEE degree from Stanford.

Kenneth J. Zdunek, Ph.D., V.P. and Chief Technology Officer
Dr. Zdunek is Vice President and the Chief Technology Officer of Roberson and Associates. He has 35 years of experience in wireless communications and public safety systems. Concurrently he is a research faculty member in Electrical Engineering at the Illinois Institute of Technology, in Chicago, Illinois, where he conducts research in the area of dynamic spectrum access and efficient spectrum utilization, and teaches a graduate course in wireless communication system design. He is a Fellow of the IEEE, recognized for his leadership in integrating voice and data in wireless networks. Prior

to joining Roberson and Associates, he was VP of Networks Research at Motorola, a position he held for 9 years. Dr. Zdunek was awarded Motorola's patent of the year award in 2002 for a voice-data integration approach that is licensed and extensively used in GSM GPRS. He holds 17 other patents, included patents used in public safety trunked systems and cellular and trunked systems roaming. He directed the invention and validation of Nextel's iDEN™ voice-data air interface and IP based roaming approach, and was the principal architect of Motorola's SmartNet™ public safety trunking protocol suite. In the 1990's, he directed a Spectrum Utilization and Public Safety Spectrum Needs Projection submitted to the FCC in support of the 700 MHz spectrum allocation for Public Safety. He was awarded the BSEE and MSEE degrees from Northwestern University, and the Ph.D. EE degree from the Illinois Institute of Technology. He is a registered Professional Engineer in the State of Illinois.

Suresh R. Borkar, Ph.D. Senior Principal Investigator

Dr. Borkar is a Senior Principal Investigator at Roberson and Associates and a member of the faculty in the Electrical and Computer Engineering (ECE) department at the Illinois Institute of Technology (IIT), Chicago. Previously, he was with AT&T/Lucent Technologies/Alcatel-Lucent (ALU) for over 26 years responsible for various facets of product management, systems engineering, architecture, development, integration and testing, and customer management in Computer and Networking systems, Wireline Switching systems, Data systems, and Wireless systems. He was the Director for Customer Management for 3G mobility systems responsible for customer positioning, acceptance, and revenue realization. He was previously the Chief Technology Officer (CTO) and Managing Director, Lucent India Inc., responsible for all Lucent customer products and business activities in India. Dr. Borkar develops knowledge share and teaches advanced courses in Telecommunications and Computer Architecture for the Academia, IEEE, and the industry. He has been an organizer and moderator of conferences and panel discussions on WiMAX and VoIP/Next Generation Networks (NGNs). Dr. Borkar received his B. Tech. in Electrical Engineering from Indian Institute of Technology Delhi (India) and M.S. and Ph. D. in ECE from Illinois Institute of Technology, Chicago.